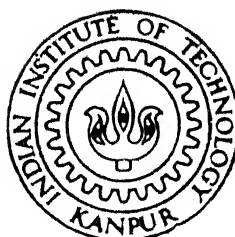# MODELLING OF CO-INJECTION OF COAL AND LIME THROUGH TUYERS OF A BLAST FURNACE

by

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INDIAN INSTITUTE OF TECHNOLOGY KANPUR

APRIL, 1998

MODELLING OF CO-INJECTION OF COAL AND LIME THROUGH TUYERES OF A BLAST FURNACE

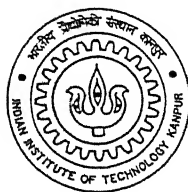## (TISCO SPONSORED RESEARCH)

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to the

DEPARTMENT OF MATERIALS AND METALLURGICAL ENGINEERING

INDIAN INSTITUTE OF TECHNOLOGY KANPUR
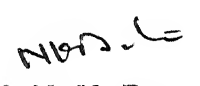
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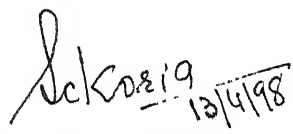
CERTIFICATE

It is certified that the work contained in the thesis entitled **MODELLING OF CO-INJECTION OF COAL AND LIME THROUGH TUYERES OF A BLAST FURNACE** by **Brijesh Singh**, has been carried out under our supervision and that this work has not been submitted elsewhere for a degree.

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Dedicated to -

My Parents

Acknowledgements

Abstract

Modelling of blast furnace ironmaking has been carried out in four stages in the present work. Modelling of the raceway region enables to determine required blast humidity to maintain certain adiabatic flame temperature. Blast temperature, oxygen enrichment of the blast, pulverised coal injection rate, lime to coal weight ratio, ash in coke and degree of gasification of silica etc. have been considered as operating variables. Second stage of modelling includes heat and mass balances in the lower part of the blast furnace comprising of the hearth and bosh regions. It is aimed at finding the fuel rate to meet the heat demand of the furnace. Operating variables include the parameters mentioned for the first stage of modelling, shaft efficiency, heat losses and reserve zone temperature of gas and solid phase etc. Third stage of modelling is carried out to determine the amount, composition and temperature of outgoing gases. This helps to test the validity of the model by comparing the computed results with the plant data. Fourth stage of modelling allows to determine the amount and composition of intermediate slags formed in the bosh region. Injection of coal and lime would result in lowering of blast humidity to maintain the constant flame temperature. This, in turn, may decrease the fuel rate marginally. Replacement ratio is found to be around 1.1 kg of coke per kg of coal injected. Injection of lime through tuyeres decreases the lime to silica weight ratio of the bosh slag. This, in turn, would help to improve the permeability of the bed and increase the productivity of the furnace. By maintaining lime to coal weight ratio of 0.2 at pulverised coal injection level of around 130 kg/thm. Computed basicity of the bosh slag decreases from 1.5 to 1.15 approximately and melting point of the bosh slag is lowered from 1690°C to 1540°C. Factors that favour

complete combustion of coal particles as well as complete dissolution of lime particles into the slag in the vicinity of the raceway must be studied carefully to take maximum advantages of Co-Injection of coal and lime through tuyeres of a blast furnace.

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Nomenclature

a_1^s : $SiO_2(\%)$ in ash

a_2^s : $Fe_2O_3(\%)$ in ash

a_3^2 : $Al_2O_3(\%)$ in ash

A_1 : ash(%) in coal

A_2 : ash(%) in coke

B_1 : amt. of SiO_2 in the bosh slag (kg/thm)

B_2 : amt. of CaO in the bosh slag (kg/thm)

B_3 : amt. of MgO in the bosh slag (kg/thm)

B_4 : amt. of Al_2O_3 in the bosh slag (kg/thm)

B_5 : amt. of MnO in the bosh slag (kg/thm)

C_1 : carbon(%) in coal

C_2 : carbon(%) in coke

C_1^s : amt. of SiO_2 in the cast slag (kg/thm)

C_2^s : amt. of CaO in the cast slag (kg/thm)

C_3^s : amt. of MgO in the cast slag (kg/thm)

C_4^s : amt. of Al_2O_3 in the cast slag (kg/thm)

C_5^s : amt. of MnO in the cast slag (kg/thm)

f :   fraction of silica reduced

f_c :   wt. fraction of carbon in hot metal

f_{mn} .   wt. fraction of Mn in hot metal

f_p :   wt. fraction of P in hot metal

f_{si} :   wt. fraction of Si in hot metal

H_1 :   hydrogen(%) in coal

H_f^i :   Heat of formation of species ' i '

H_i^T :   Sensible heat of species ' i ' at T°k

H_{ss} :   Sensible heat of solid slag

H_{ls} :   Sensible heat of liquid slag

H_{lo} :   External furnace heat losses (cal/mole blast)

$H_{vp}^{H_2O}$:   Heat of vapourisation of H_2O

L_1 : $CaCO_3$(%) in lime

L_2 : SiO_2(%) in lime

L_3 : CaO(%) in lime

L_4 :   MgO(%) in lime

L_5 : Al_2O_3(%) in lime

M_2 :   moisture(%) in coke

n_{N_2} :   moles/mole blast of N_2 in raceway gases

n_{H_2} :   moles/mole blast of H_2 in raceway gases

n_{CO} :   moles/mole blast of CO in raceway gases

n_{SiO} :   moles/mole blast of SiO in raceway gases

n_{SiO_2} moles/mole blast of SiO_2 in raceway

n_{CaO} : moles/mole blast of CaO in raceway

n_{MgO} : moles/mole blast of MgO in raceway

$n_{Al_2O_3}$: moles/mole blast of Al_2O_3 in raceway

n_{Fe} . moles/mole blast of Fe in raceway

N_1 : nitrogen(%) in coal

N_{N_2} : amt. of N_2 in the top gas (kmoles/thm)

N_{CO} : amt. of CO in the top gas (kmoles/thm)

N_{CO_2} : amt. of CO_2 in the top gas (kmoles/thm)

N_{H_2} : amt. of H_2 in the top gas (kmoles/thm)

N_{H_2O} : amt. of H_2O in the top gas (kmoles/thm)

O_1 : oxygen(%) in coal

O_e : amt. of O_2 in the blast $= 0.21 + \frac{(\%O_2 enrichment)}{100}$

or_1 : SiO_2(%) in iron ore

or_2 : CaO(%) in iron ore

or_3 : MgO(%) in iron ore

or_4 : Al_2O_3(%) in iron ore

or_5 : Fe(%) in iron ore

P_1 : moles/mole blast of Nitrogen in the bosh gases

P_2 : moles/mole blast of Hydrogen in the bosh gases

P_4 : moles/mole blast of FeO coming into the bosh region

P_5 : wt. of last slag (g/mole blast) produced

P_6 : wt. of hot metal (g/mole blast) produced

P_7 : moles/mole of CO in the bosh gases

P_8 : moles/mole of Fe coming into the bosh region

P_{or} : pct. ore in burden

P_{sn} . pct. sinter in burden

q_1 : wt. of coal injected (kg/thm)

q_2 : wt. of coke injected (kg/thm)

q_3 : wt. of lime injected (kg/thm)

q_4 : amt. of dry blast (kmoles/thm)

q_5 : wt. of cast slag produced(kg/thm)

q_6 : amt. of moisture in the blast (kmoles/thm)

q_7 : amt. of iron incoming to the bosh (kmoles/thm)

q_8 : wt. of burden (kg/thm)

q_{or} : wt. of iron ore in the burden (kg/thm)

q_{sn} : wt. of sinter in the burden (kg/thm)

q_{10} : amt. of Fe_2O_3 in the coal injected(kmoles/thm)

q_{11} : amt. of Fe_2O_3 in the coke charged(kmoles/thm)

q_{12} : wt. of cast slag (kg/thm)

q_{13} : basicity of cast slag

q_{14} : wt. of slag formed in the raceway (kg/thm)

q_{15} : wt. of slag formed in the bosh (kg/thm)

q_{16} : basicity of bosh slag

R_1 .   amt. of SiO_2 in the raceway slag (kg/thm)

R_2 ·   amt. of CaO in the raceway slag (kg/thm)

R_3 :   amt. of MgO in the raceway slag (kg/thm)

R_4 :   amt. of Al_2O_3 in the raceway slag (kg/thm)

R_{cg} :   rate of N_2 gas carrying coal and lime (1.12×10^6) moles/g)

S_1 :   % of FeO in cast slag

sn_1 : $SiO_2(\%)$ in sinter

sn_2 : $CaO(\%)$ in sinter

sn_3 : $MgO(\%)$ in sinter

sn_4 : $Al_2O_3(\%)$ in sinter

sn_5 : $Fe(\%)$ in sinter

sn_6 : $FeO(\%)$ in sinter

T_f :   Raceway adiabatic flame temperature (^{o}K)

T_b :   Blast temperature (^{o}K)

T_c :   Preheat solid coke temperature coming to the raceway (^{o}K)

T_{se} :   Reserve zone solid temperature (^{o}K)

T_{ge} :   Reserve zone gas temperature (^{o}K)

T_{tg} :   Top gas temperature (^{o}K)

W_1 :   wt. of coal (g)

W_2 :   wt. of solid coke (g/mole blast) descending to the raceway

W_{2b} :   wt. of coke (g/mole blast) coming into the bosh region.

W_3 :   wt. of lime (g)

W_{Fe} :   wt. of iron (g/mole blast) being reduced in the raceway

$(W_{mn})_{HM}$:   wt of Mn in hot metal

$(W_{mn})_{slag}$:   wt. of Mn in slag

W_{slag} :   wt. of slag(g/mole blast) forming in the raceway

x :   moles/mole blast of H_2O in the blast

Chapter 1

INTRODUCTION

For many years, production of hot metal and steel has been subjected to increasing costs in the markets all over the world. Awareness concerning pollution of the environment has also been growing. The coke making process being connected with the blast furnace operation requires high expenditures regarding personnel and plant investment and is, moreover, polluting the environment. Furthermore, coking coal supply is limited and in some cases must be purchased only by foreign currency. The scarcity of low ash coking coals coupled with the competition in blast furnace ironmaking, have forced ironmakers to innovate techniques to lower coke rate and produce high quality metal. Pulverised coal injection (PCI) is a notable innovation invented in the world. The pulverised coal injection in blast furnace is one of the fastest expanding development in the field of ironmaking because of the following:

1. Pulverised coal is cheaper than coke resulting in improved economics.

2. The capital cost of PCI is less than the coke oven plant on the basis of an equivalent unit of blast furnace fuel. The cost of PCI plant including preparation plant may be Rs.1,500/- to Rs.2,300/- per annual tonne compare to Rs.3,500/- to Rs.4,000/- for the new coke oven plant[1].

3. A wide range of coal types from lignite to anthracite have been injected successfully with the ash level varying from 3 to 18 %[1].

4. Conservation of coking coals will sustain the steel industry for longer periods.

5 The coal injection decreases the raceway flame temperature allowing increase in blast temperature and oxygen enrichment thus intensifying the blast furnace operation and maximising the productivity.

6. The coal injection leads to smoother furnace operation with less hanging and slipping as compared to all coke operation and it gives quick response to change in furnace operation.

Injection of pulverised coal through the tuyeres into a blast furnace is being practised on a global scale these days to improve the stability and reduce the cost of blast furnace Ironmaking. It replaces the coke from the burden to a certain extent, and it is very significant especially from the view point of economics and environmental standards. Further reduction in the cost of steel making may occur due to lowering of the silicon and sulphur content in hot metal in the blast furnace. One of the means for simultaneous reduction of silicon and sulphur contents in pig iron is the flux injection into blast furnace. Lime injection is favoured to achieve following benefits:

- Insitu fluxing of silica in the coke.

- To lower basicity of slag in the bosh region.

- To improve fluidity of the bosh slag.

- To reduce flooding related problems.

- To improve blast furnace productivity due to higher driving rates.

- To reduce silicon transfer to metal.

- Better control of sulphur in hot metal.

With injection of pulverised coal and lime or dolime, the heat locally generated from pulverised coal combustion is transferred to nearby injected lime.

Today more than 100 blast furnaces all over the world are equipped with coal injection facilities. Tata steel commissioned a coal injection unit in March, 1991 in the F blast furnace. The system developed by Klockener stahl technik(KST) Fig 1.1[2] was adopted. It is capable of an injection rate up to 150 kg/thm.

The present work was undertaken to study the effects of coal and lime injection on the performance of the blast furnace. Stage wise modelling of the furnace based on material and enthalpy balances has been carried out to study the effects of various parameters on the fuel rate and bosh slag characteristics
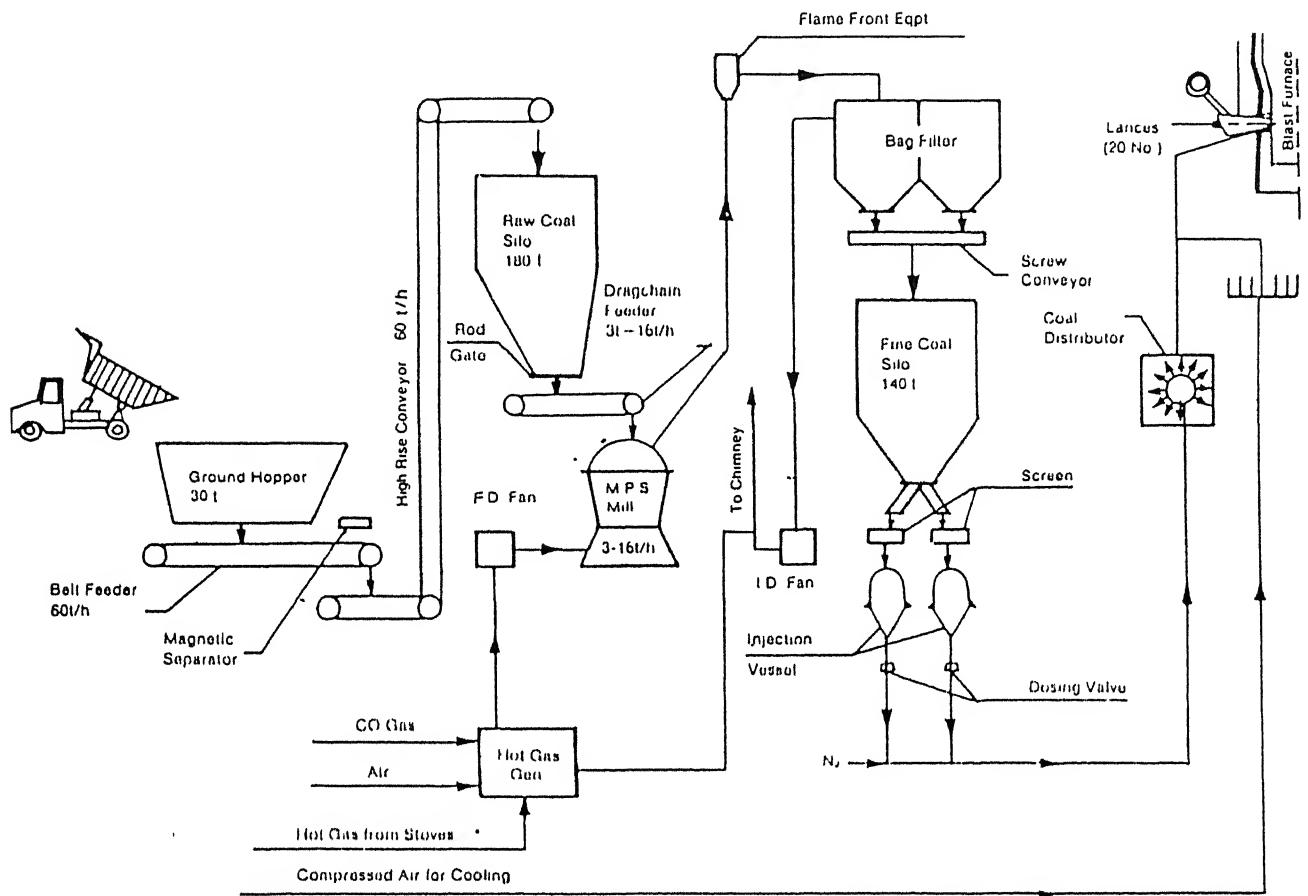
Figure 1.1: Flow diagram of the KST coal injection system

Chapter 2

LITERATURE REVIEW

2.1 Preamble

Recently coal injection in blast furnaces has been adopted for decreasing the coke rate to the lowest possible extent commensurate with the furnace thermal balance and raceway conditions. A summary of plants where the technology has been in use is included in Table 2.1. A variety of coal injection systems have been developed to handle various types of coals ranging in size from pulverised to granular[20].

Most of the systems developed have performed well, achieving 0.8 to 0.9 tons of coke replacement by 1.0 tonne of coal. The extent of coal injection is limited by the plant and process engineering considerations. Therefore, it should be ensured at the planning stage itself that the plant engineering permits high injection rates. System designs equipped with flow regulation using either individual or uniform tuyere systems are available today which can inject coal up to 200kg/thm. It is, thus, possible from the plant engineering point of view to inject coal with a uniform distribution at high rates. Process engineering limits may be imposed due to incomplete coal combustion during injection. This combustion is influenced mainly by coal quality, oxygen to carbon atom ratio during combustion and the blast furnace operating conditions. The basic

and pilot plant studies as well as the operating experiences of the furnaces where coal injection technology has been adopted are reviewed in this chapter.

2.2 Coal injection system

A complete coal injection system is shown in Fig 1.1. It comprises of the following units:

1. Coal receiving and storage unit.

2. Drying and pulverising unit.

3. Injection unit.

The details of each of the above units have been described by Taneja[2] and are summarised below.

2.2.1 Coal receiving and storage unit

Coal for injection is transported from the yard to the ground hopper by dumpers. The coal is conveyed to the raw coal bin by a vertical flexo-well conveyor.

2.2.2 Drying and pulverising unit

The coal being supplied generally has a moisture content of up to 12 % against a desired value of less than 1 %. Therefore, drying and pulverising of the coal are carried out simultaneously in the coal grinding mill which is injected with hot gases(Fig 1.1). Hot gases are usually supplied by a hot gas generator which uses coke oven gas, natural gas or oil as the heating medium.

Table 2.1: Present status of coal injection

Plant	Country	Production (t/day)	Coal Injection Rate (kg/ton)	Year
Inland Steel Co.	U.S.A.	8655	150	-
Arbed-Belvel[3]	Luxemburg	2126	75.8	1980
Acesita[4]	Italy	5000	170	1981
Cleveland[5] Iron works	Netherland	2.4	259	1981
Oita works[6] Nippon Steel Corporation	Japan	8500	52	1982
Kobe Steel Ltd. (Kakogawa)[7]	Japan	8000	200	1983
SSAB Lulea[8]	Germany	9000	140	1983
Shoudu Iron and Steel Company[9]	China	8564	137.1	1984
Wuhan Iron and Steel Company[10]	China	-	175-220	1986-87
Sidmar[11]	Belgium	4250	117	1988
Mizushima No.4[12]	Japan	10658	70-90	1989
Sollac	France	8814	160	1990
Kimitsu No.4[13]	Japan	9567	132	1990
Hoogovens[14]	Netherland	8228	175-212	1991
Kokura[15]	Japan	-	150	1991

Plant	Country	Production (t/day)	Coal Injection Rate (kg/ton)	Year
Thyssen[16]	Germany	8915	173	1991
Gary B.F 4[17]	U.S.A.	-	160	1993
Taranto Works[18]	Italy	5000-6000	200	1994
TISCO[19]	India	2972	122	1996

To save energy, the waste gases from the stoves of the blast furnaces are also used for the drying operation. The inert nature of the gases helps in maintaining the oxygen content at low levels.

Temperature of the hot gases entering pulveriser varies from 150 to 300 °C. The outlet temperature from the mill is 90 °C, and the moisture content of pulverised coal is 1 % or less.

Grinding of coal in the mill is carried out by stream of hot gases flowing upwards through nozzles positioned around the rotating table. The hot gases also remove the moisture from the coal and help to keep the partially ground coal circulating in the grinding zone. A static classifier with a system of adjustable vanes to vary the pulverised coal fineness is mounted directly on the top of the mill. Oversize particles fall to the bottom of the cone in a similar manner to that in a cyclone. The mill is designed to avoid fires and to contain explosions.

The coal is fed into the mill by a drag chain conveyor which is provided with a variable frequency drive to adjust the rate of coal feeding. Different plants use hammer mills, horizontal ball crushers and vertical ball grinding mills for grinding as shown in Table 2.2, depending on installation and operating costs.

2.2.3   Injection unit

The injection unit mainly consists of pressure vessels and lance.

2.2.3.1   Pressure vessels

The coal from the fine coal silo falls into a vibrating sieve through the silo output valve. The undersize of this vibrating sieve falls into the pressure vessel through the pressure vessel inlet valve. The vent valve on the pressure vessel remains open during the filling of the vessel. When the vessel is filled all the aforementioned valves (silo outlet valve, inlet valve and vent valve) are

Table 2.2: Different types of grinding mills used in different plants

Plant	Drying Medium	Grinding Mill
KST	Hot stove waste gas	M.P.S. mill
ARMCO	Natural gas/Hot stove waste gas	Bowl mill
K-BFI	Stove waste gas/Natural gas	Vertical ball mill
KOBELCO	Hot Stove waste gas	Roller mill
TARANTO	Blast furnace gas/Cowper gas	Vertical Roller mill
SHOUDU	-	Ball mill
HOOGOVENS	Natural gas	-
ACESITA	-	Vertical Ball mill

closed and the vessel is pressurised to 90 % of the nominal pressure so that it becomes ready for injection. Since there are two pressure vessels which work alternatingly, the pressure vessel which is ready for injection waits for the zero weight or minimum weight signal from the other vessel. As soon as this signal is received, hydraulically operated dozing valve at the outlet of the pressure vessel opens and the fines are transported pneumatically through pressurised fluidisation for injection. It follows naturally then that the outlet/dozing valve of the other pressure vessel closes and the procedure of filling, pressurising and waiting is repeated for this vessel, though in order to maintain continuity during dozing, the dozing valve of the second pressure vessel closes only after the dozing valve of the first pressure vessel has opened by 25 %. The dozing valve allows injection to be performed according to a preset rate. The coal flows through a single pipeline into the coal distributor located near the cast house of the furnace. From the distributor, individual lines are taken to the tuyeres. These lines have the same number of bends and the same length to ensure almost equal distribution to the tuyeres and the deviation from tuyere to tuyere is within 5 %.

2.2.3.2   Lance

To enhance the efficiency of combustion, location of the injection lance is extremely important as it controls the mixing of coal particles with the blast. When the lance is located upstream from the tuyeres, the combustion efficiency improves but when the lance is moved too far upstream, there is no further improvement in combustion but ash will be deposited on the inner surface of the blow pipe and tuyeres (Fig 2.1) this causes clogging of the blast passage. The optimum location is dependent on the type of coal, the blast temperature, particle size and shape of the lance[21].

The coal stream immediately gets diverted along the direction of the hot blast irrespective of the inclination of the lance. Diameter of the lance used is generally 12 -15 mm. In most cases, the lance enters the blow pipe at a shallow angle, which maintains a narrow plume of coal in the tuyeres. A central plume
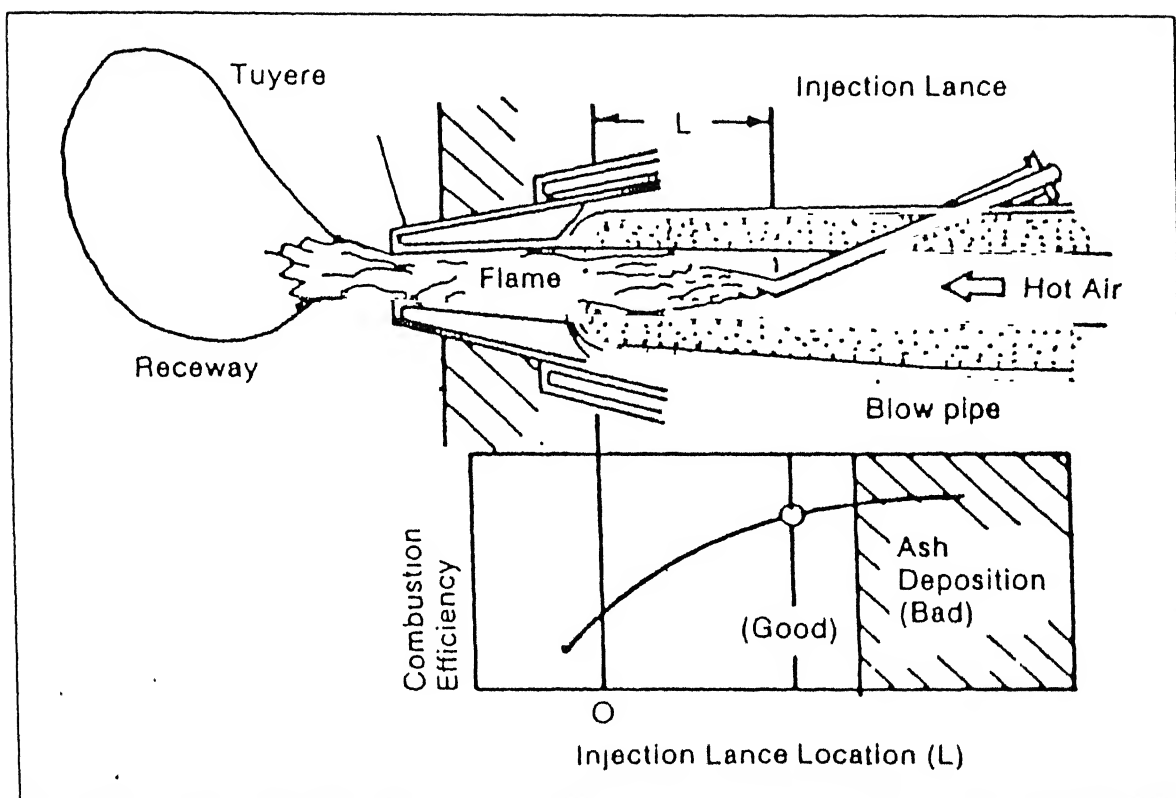
Figure 2.1: Effect of lance position on combustion efficiency and ash deposition in the blow pipe

will minimise mechanical erosion of the tuyeres.

Problem of ash deposition in the blow pipe with high ash content of coal have to be tackled by optimising the lance location. The desirable properties of coal described by Bhanu are[22] are as follows:

- Ash content : Less than 10 %.

- Fusion temperature : It should be greater than 1400 °C.

- Volatile Matter : It should be greater than 30 %.

- Size · 80 % coal must pass through 200 mesh size.

2.3   Safety precautions

The following precautions are necessary to ensure safety of the system :

1. Pulverised coal storage reservoir should be inert(non- oxidising).

2. Build-up any of static electricity should be avoided i.e. all the equipments should be grounded.

3. Sparks should be avoided.

4. The oxygen and CO level should be monitored. Oxygen content should not exceed 8-10 %. Otherwise emergency nitrogen purging should be started.

2.4 Factors affecting coal combustion

2.4.1 Volatile matter

Low rank coals with high volatile matter contents give better efficiency of combustion, this may be a parameter which ultimately decides the suitability of any coal for combustion[23].

Rapid devolatisation of coal results in a higher degree burnout in the blow pipe. This in turn can increase sharply the temperature of gases in the blow pipe. Coals with low volatile matter have high carbon to hydrogen ratios and they give a high replacement ratio. But, generally high or medium volatile coal is preferred for injection purposes since their combustion efficiency is reported to be high.

Tadehara et al.[7] have studied combustion efficiency of various coals having different volatile matter as a function of axial distance from tuyere. the results are shown in Fig 2.2. According to them coals with volatile matter approximately 40 % has higher combustion efficiency as compared with coals having 20 % volatile matter.

Tar produced during pyrolysis of coal decomposes to soot during combustion. Hunty et al.[24] has reported that in the temperature range 1600-2000 °C about one third of mass of volatiles is transformed to soot. Tar and soot are undesirable materials in the blast furnace. Soot is less reactive than residual char and complete combustion demands a high air/fuel ratio and a long residence time not available during coal injection. Soot can cause an increased fuel rate and many serious operating problems such as blockage of raceways, decreased burden permeability. undesirable temperature distribution with in the furnace, and hanging and rolling of the burden. Thus generation of tar during pyrolysis of certain high volatile matter coals is detrimental.

Although coals with volatile matter contents of about 25-30 % are preferable. the amount of volatile matter in coal should not exceed 35 % as there is a

chance of explosion. Further storage and transportation of such coals would be difficult owing to the problem of spontaneous combustion, particularly in dry months.

2.4.2   Particle size

The particle size of coal is important for achieving the desired degree of combustion in the raceway zone. If the combustion is not proper, then the particles would get swept into the burden and interfere with the gas flow. The upper size limit for pneumatic conveyance of coal through a tuyere is governed by the maximum lance diameter which can be inserted through the side of a blow pipe without unduly obstructing the flow of the hot blast. Generally, the smaller the grainsize of coal, the greater is the degree of combustion, due to more exposed surface area. It is reported by Wakuri that, if the particle size of the pulverised coal is 100 μ m or less, and the volatile content is 25 % or more, then its combustibility is usually good[6]. According to O'hanlon at least a 5·1 ratio of pipe diameter to particle diameter is acceptable for injection[25].

2.4.3   Blast parameters

The combustion efficiency increases with an increase in blast temperature. The effect is more pronounced in the temperature range of 1000-1100 °C and wears down above 1150 °C, Shyuki, 1985[21] and Wakuri, 1983[6].

Pandey[26] has reported that under blast furnace conditions the combustion efficiency of coal improves more effectively by increasing the oxygen content of the blast than by raising the blast temperature.

According to Ueno[27] the combustion efficiency increases slightly with increase in blast humidity, due to reaction of char and steam. The addition of steam theoretically lowers the flame temperature, it must be accompanied by increase in blast temperature or O_2 enrichment.
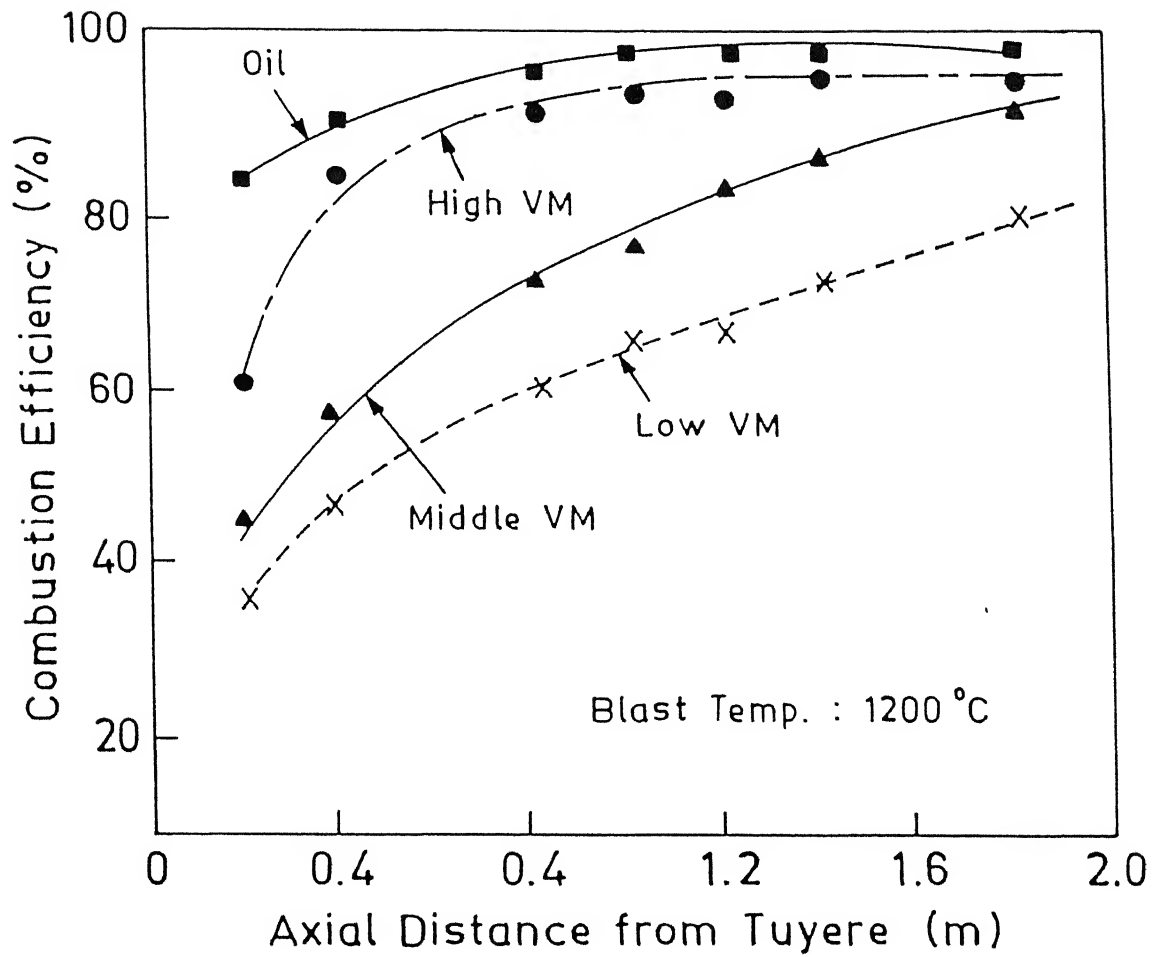
Fig. 2.2. Relationship of Volatile Matter Content of Injected Coal and the Combustion Efficiency.

2.4.4   Oxygen to Carbon ratio

Carbon is oxidised to CO gas in the raceway. This requires overall carbon to oxygen atom ratio of 1.0 in the gas phase. A part of carbon that is combusted comes from the coal and rest is from the coke. According to Peters et al [16] the limit of coal injection is reached when blast oxygen to coal carbon ratio is 2.1. It is equivalent to coal injection rate of about 150 kg/ton hot metal.

2.5   Effect of coal injection on blast furnace operation

Typical operating data for some of the blast furnaces where the coal injection technology has been practised, are included in Table 2.3. The experiences gained by the plants from running of different blast furnaces are summarised below in this section. The most likely parameter to be affected by coal injection would be permeability. Studies by Goncalves[4] have shown that the permeability of the No.1 blast furnace at Acesita experienced a downward trend with coal injection. Burden permeability was found to decrease when coal injection was increased from 115 kg/ton to 165 kg/ton.

Silicon content in pig iron decreased from 0.72 % to 0.45 % when coal injection rate was increased from 30 kg/t to 150 kg/t at Acesita works.

At Arbed-belval interesting observations have been reported by Koster[3]. Upon coal injection, there was no significant decrease in overall permeability though a slight decrease was reported in the bosh region. There was also no improvement in the productivity. However, the adiabatic flame temperature dropped by 1.5 to 2 °K per gram of coal injected. One encouraging result of coal injection was significant improvement in the quality of hot metal with respect to low sulphur content, a phenomenon which is not clearly understood and can be a subject of further research.

Nippon steel has successfully adopted PCI technology developed by Armco,

Table 2.3:

Plant	Hearth dia. (m)	Blast Temperature (°C)	Adiabatic Flame Temperature Temperature(°K)	Replacement Ratio
Arbed-Belvel[3]	8	1132	-	0.81
Cleveland Iron works[5] (pilot plant)	0.5	870	2175	-
Oita works Nippon Steel Corporation[6]	14.2	1290	2300-2350	1.025-1.2
Kobe Steel Ltd. (Kakogawa)[7]	13.2	1250-1300	-	0.88
Taranto Works[18]	-	1163	2200-2300	0.8-0.88
Hoogovens[14]	13.5	1250	2150-2350	0.9-0.95

Babcock and Wilocox for its use in large blast furnaces. Wakuri et al.[6] have reported about the performance of no.1 blast furnace at Oita works which is based on technology used at Amanda blast furnace at Armco's Ashland works. The analysis of high speed films showed that most of the coal injected burned up within a millisecond, i.e. before it had passed into the raceway. The injection rate was increased in three steps. First an injection rate of 30 to 40 kg/t was attained, then it was increased to 50 to 55 kg/t, and later 80 to 100 kg/t. Each injection rate was maintained for two months or longer to stabilize the operation. The most notable changes brought about by introduction of Pulverised coal injection were:

1. Increase in productivity.

2. Constant blast temperature of 1300°C.

3. Decrease of blast humidity from 30 to 10 g/Nm^3.

4. Increase of ore/coke ratio from 3.5 to 4.25.

5. Hanging of blast furnace was eliminated.

Catastrophic tuyere failures, furnace hanging and variations in replacement ratio were major problems encountered at the National steel and Bruceton furnaces as reported by Ostrowski[28]. Tuyere failure at Weirton No. 3 and No.4 blast furnace due to coal injection was reported. It was observed in 21 weeks time, that no. of tuyeres damaged increased from 50 without coal to 169 with coal. Many a time slag and metal oozed out of the furnace through the tuyere cooler and the blow pipe. The severity of problem was further increased by reducing the air volume which resulted in filling up of blow pipes.

Ostrowski[28] also reported that a significant hanging occurred at Bruceton blast furnace due to Pulverised coal injection. By reducing blast pressure, hanging could be overcome. Ostrowski[28] reported further that injection rate, blast temperature, blast oxygen, blast moisture and the degree of coal powder burning infront of tuyeres govern the replacement ratio.

Eichinger et al.[29] has reported the effect of coal injection on the performance of blast furnace in Taranto(ILVA). Alongwith 20 % reduction in coke consumption, productivity increased from 57 to 62 $thm/m^2/day$ with introduction of Pulverised coal injection. Initially oxygen enrichment of the blast was maintained at high level due to operation safety but to abate the hot metal cost, this was reduced.

Brouwer[14] reported that the performance of blast furnace in Hoogovens greatly improved, as a result of coal injection in terms of economy and hot metal quality etc. Blast furnace production capacity increased by approximately 10 % compared to an all-coke practice due to the decreased blast consumption. Coal injection levels up to 160 to 180 kg/ton hot metal could be handled without special burden and coke quality requirements. For injection levels of 200 kg/ton of hot metal and above, specific problems occurred in running the furnace.

Bocong et al.[9] have repoted on the experiences of Shoudu iron and steel company that varieties and qualities such as fineness of coal particles, the operational technique of the furnace and injection system influence replacement ratio. A high quality fine coal with low ash content accelerated the combustion. Moreover, the replacement ratio is also dependent on theoretical combustion temperature and gas flow distribution.

Chapter 3

PLAN OF THE PRESENT WORK

The main objective of the present work is to analyse the effect of pulverised coal injection along with powdered lime through the tuyeres into the blast furnace, on various parameters like coke rate, top gas composition and temperature, allowable blast humidity, slag rate and basicity etc. The study has been divided into following four stages:

1. RACEWAY REGION

2. LOWER PART OF FURNACE

3. OVERALL MASS AND HEAT BALANCE

4. BOSH REGION

Modelling of raceway region was aimed at finding the required blast humidity to maintain the adiabatic flame temperature for specified parameters. The lower part of furnace is considered to be more critical from heat point of view than the upper part. Heat and mass balance in the lower part have been used to determine the required fuel rate for certain raw materials and blast parameters. Overall heat and mass balance of the furnace has been used to

determine the top gas volume, composition and temperature. Fourth stage is an extension of second stage which uses only material balance to find the amount and composition of slag formed in the bosh region of the furnace. Mathematical model and the computer programme to find the solution have been tested using data from literature as well as data collected from G blast furnace of Tata Iron and steel company, Jamshedpur. Practical importance of the study is highlighted.

Chapter 4

MODEL EQUATIONS

4.1   Introduction

Mathematical model equations are developed in this chapter to determine the adiabatic flame temperature, fuel rate, slag rate, burden weights, top gas composition and temperature. The work has been carried out in different stages, starting from the raceway region to the blast furnace taken as a single unit for making material and enthalpy balances. At each stage of work, certain assumptions and simplifications of the process are made.

4.2   Mathematical Modelling of Raceway:

4.2.1   Introduction

Metal and slag temperatures in the hearth are determined to a great extent by the maximum temperature attained by the gases at the edge of raceway in front of the tuyeres of a blast furnace. Many controls in the blast furnace are necessarily based on keeping the flame temperature in the narrow temperature range by adjusting the operating parameters such as blast temperature. blast humidity and oxygen enrichment of the blast. A mathematical model, to deter-

mine the effect of operating variables on the calculations of flame temperature is described in this section.

Raceway is a pear shaped high temperature zone in the vicinity of tuyeres. Preheated coke particles descend through the bosh to reach raceway. Pulverised coal may be injected through the tuyeres along with the blast. Carbon in the coal and coke takes part in the combustion reaction with stoichiometric amount of oxygen coming with the preheated air blast. Raceway region may consist of an oxidising zone where carbon is first converted to carbon dioxide and a reducing zone where carbon dioxide, thus formed as well as water vapours present in the blast in the gases react with carbon to form carbon monooxide and hydrogen. Any hydrocarbons present in the pulverised coal and undecomposed carbonates present in lime that are injected through the tuyere would dissociate in the raceway. Ash in coke and coal would combine with lime to form slag. However, a part of silica in ash may undergo a partial reduction at such a high temperature to form silicon monoxide gas. Ash may contain a little amount of haematite(Fe_2O_3), which is reduced to iron. Rest of ash along with lime forms a part of slag.

Species that enter and leave the raceway are shown schematically in Fig 4.1.

4.2.2 Assumptions:

1. There is no heat loss in the raceway.

2. Incoming solid coke is preheated to 1500 °C before reaching the raceway.

3. Fraction of silica being gasified is empirically assumed.

4. Combustion efficiency of coal is 100%.

5. Molten slag and hot metal descending through the bosh to the hearth, do not come in contact of the raceway.
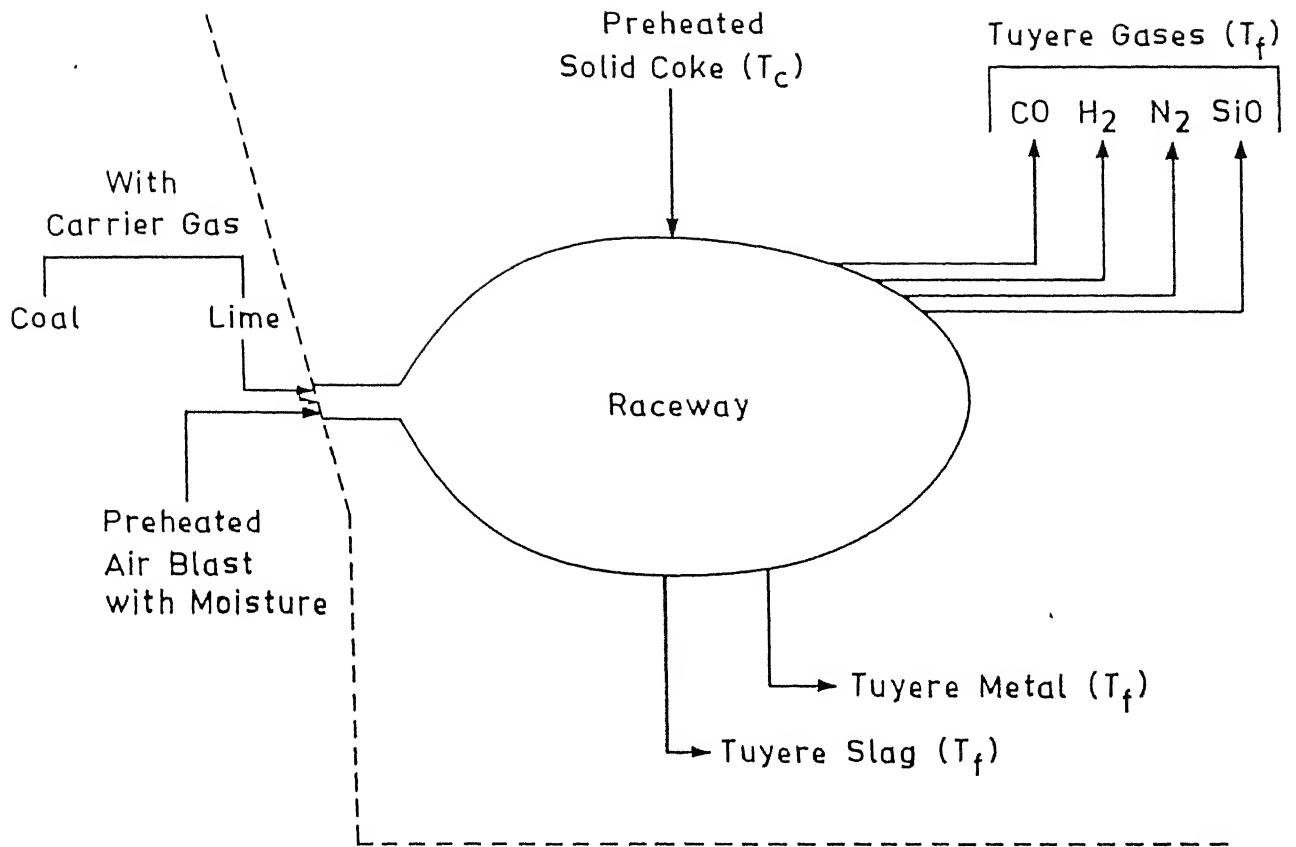
Fig. 4.1. Schematic of Material Flow in the Raceway Region of the Blast Fúrnace .

6. Silica in the lime injected through the tuyeres is not reduced in the raceway.

7. Sensible heats of slag and molten iron are assumed to be independent of the composition of these phases and are determined by empirical correlations.

8. Sensible heat of the coal and the carrier gas are ignored.

9. Heat of cracking of coal is determined from its ultimate analysis as follows:

   - Any dissociable oxygen present in coal is assumed to be present with hydrogen as H_2O.

   - Remaining amount of dissociable hydrogen is assumed to be present as CH_2.

   - Enthalpy change due to transfer of sulphur and nitrogen for solid to gas phase are ignored.

4.2.3 Overall Reactions

Overall reactions occuring in the raceway may be described as follows:

1. Oxidation of carbon by oxygen and moisture in the blast.

$$C + (\frac{1}{2})O_2(g) \rightleftharpoons CO(g) \qquad (4.1)$$

$$C + H_2O(g) \rightleftharpoons CO(g) + H_2(g) \qquad (4.2)$$
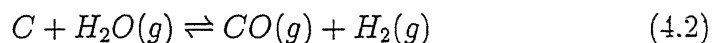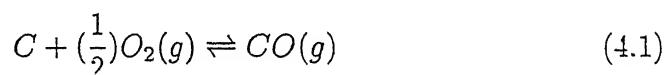
2. Reduction of SiO_2

$$SiO_2 + C \rightleftharpoons CO(g) + SiO(g) \qquad (4.3)$$
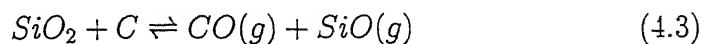
3. Calcination of undecomposed Lime

$$CaCO_3 + C \rightleftharpoons CaO + 2CO(g) \qquad (4.4)$$
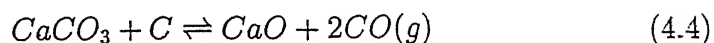
4. Reduction of Iron oxide present in the coke and coal.

$$Fe_2O_3 + 3C \rightleftharpoons 2Fe + 3CO(g) \qquad (4.5)$$
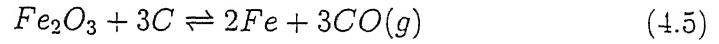
Mathematical Modelling of Raceway is divided into two parts as follows:

1. The blast parameters are specified and the model aims at finding the adiabatic flame temperature.

2. The flame temperature reached by tuyere gases is specified and model aims at finding the required moisture in the blast for specified oxygen enrichment,blast temperature and level of pulverised coal injection rate etc.

4.2.4 Model to determine adiabatic flame temperature

One mole of dry blast consisting of oxygen and nitrogen is taken as the basis. All other parameters are assumed or determined per unit of dry blast. The blast includes any oxygen that is added to enrich the air. It is necessary to determine the amount of tuyere gases such as carbon monoxide, hydrogen, nitrogen and silicon monoxide as well as the metal and slag phases that are formed in the raceway, before making any heat balance to find the temperature of the tuyere gases. The amount of coke that enters the raceway has to be determined as a function of operating parameters such as blast humidity, oxygen enrichment of blast, and amount of coal and lime that are injected with the blast. Model equations based on the balance of species such as nitrogen, hydrogen, carbon, oxygen etc. are described in Table 4.1. Symbols used are explained in nomenclature in the beginning of the thesis.

There are 10 equations with 10 unknown variables. Variables n_{N_2}, n_{H_2}, n_{CaO}, n_{MgO}, can be obtained directly from equation 1, 2, 7, 8 of Table 4.1. Equations 3, 4, 5, 6 and 10 are solved simultaneously to determine n_{CO}, n_{SiO}, n_{SiO_2}, n_{Fe} and W_2. Then the value of $n_{Al_2O_3}$ is obtained from equation 9 of Table 4.1.

Table 4.1: Equations based on Material Balance in the raceway region

S N.	Balancing species	Equation
1.	N_2	$n_{N_2} = \frac{W_1 N_1}{2800} + (1 - O_e) + (W_1 + W_3)R_{cg}$
2.	H_2	$n_{H_2} = \frac{W_1 H_1}{200} + x$
3.	C	$n_{CO} = \frac{(W_2 C_2 + W_1 C_1 + 0.12 W_3 L_1)}{1200}$
4.	O_2	$n_{CO} = \frac{3(W_1 A_1 + W_2 A_2)a_2^s}{1.6 \times 10^6} + \frac{W_1 O_1}{1600} + \frac{2(W_3 L_1)}{10000} + 2O_e + x + n_{SiO}$
5.	Si	$n_{SiO} + n_{SiO_2} = \frac{(W_1 A_1 + W_2 A_2)a_1^s}{6.0 \times 10^5} + \frac{W_3 L_2}{6000}$
6.	SiO	$n_{SiO} = \frac{(W_1 A_1 + W_2 A_2)a_1^s f}{6.0 \times 10^5}$
7.	CaO	$n_{CaO} = \frac{W_3 L_3}{5600}$
8.	MgO	$n_{MgO} = \frac{W_3 L_4}{4000}$
9.	$Al_2 O_3$	$n_{Al_2 O_3} = \frac{(W_1 A_1 + W_2 A_2)a_3^s}{1.02 \times 10^6} + \frac{W_3 L_5}{1.02 \times 10^4}$
10.	Fe	$n_{fe} = \frac{2(W_1 A_1 + W_2 A_2)a_2^s}{1.6 \times 10^6}$

Heat balance of the raceway region gives the following equation

$$
n_{CO}H_f^{CO} + n_{SiO}(H_f^{SiO} - H_f^{SiO_2}) + O_e H_{O_2}^{T_b} + (1 - O_e)H_{N_2}^{T_b}
$$
$$
+ xH_{H_2O}^{T_b} + \frac{W_2 A_2}{100} \times 0.25 \times (t_c - 298) + \frac{W_2 C_2}{1200} \times H_C^{T_c}
$$
$$
= xH_f^{H_2O} + n_{H_2}H_{H_2}^{T_f} + n_{CO}H_{CO}^{T_f} + n_{N_2}H_{N_2}^{T_f} + n_{SiO}H_{SiO}^{T_f}
$$
$$
+ n_{Fe}(10.6(T_f - 1873) + 280 \times 56) + \frac{n_{Fe}H_f^{Fe_2O_3}}{2}
$$
$$
+ (60n_{SiO_2} + 102n_{Al_2O_3} + 56n_{CaO} + 40n_{MgO})(0.25 \times (T_f - 1873) + 480)
$$
$$
+ W_1 H_{Crack} + \frac{W_3 L_1 H_f^{Cac}}{10000} \quad (4.6)
$$

This is a nonlinear equation and it can be solved by the method iteration using a computer programme

4.2.5 Model to determine blast humidity

This model is also based on unit mole of dry blast. The model equations based on heat and mass balance are similar to those as described in section 4.2.4 and are summarised in Table 4.2.

There are 8 linear equations with 8 unknown variables. Variable n_{N_2} can be obtained directly from Equation 1 of Table 4.2. Linear equations 3 to 8 of Table 4.2 are solved simultaneously to determine the unknowns x, W_2, n_{CO}, n_{SiO}, W_{Fe} and W_{slag}. Then the value n_{H_2} may be obtained from equation 2 of the Table.

4.3 Modelling of the Lower zone :

4.3.1 Introduction

In this section, lower part of the blast furnace consisting of the bosh and hearth regions is considered. The lower part is separated from the upper part by a reserve zone where the temperature of gas is close to that of solid. Haematite(Fe_2O_3) and magnetite (Fe_3O_4) are assumed to be pre reduced to

Table 4 2: Equations based on Material and Enthalpy balances in the raceway region

S.N	Balancing species	Equation
1.	N_2	$n_{N_2} = \frac{W_1 N_1}{2800} + (1 - O_e) + (W_1 + W_3)R_{cg}$
2.	H_2	$n_{H_2} = \frac{W_1 H_1}{200} + x$
3.	C	$n_{CO} = \frac{(W_2 C_2 + W_1 C_1 + 0.12 W_3 L_1)}{1200}$
4.	O_2	$n_{CO} = \frac{3(W_1 A_1 + W_2 A_2)a_2^s}{1.6 \times 10^6} + \frac{W_1 O_1}{1600} + \frac{2(W_3 L_1)}{10000} + 2O_e + x + nsio$
5.	Si	$n_{SiO} = \frac{(W_1 A_1 + W_2 A_2)a_1^s f}{6.0 \times 10^5}$
6.	Fe	$W_{Fe} = \frac{112(W_1 A_1 + W_2 A_2)a_2^s}{1.6 \times 10^6}$
7.	Slag	$W_{Slag} + 60 n_{SiO} = \frac{(W_1 A_1 + W_2 A_2)(1 - 0.01 a_2^s)}{100} + \frac{W_3(100 - 0.44 L_1)}{100}$
8.	Enthalpy	$n_{CO} H_f^{CO} + n_{SiO}(H_f^{SiO} - H_f^{SiO_2}) + O_e H_{O_2}^{T_b} + (1 - O_e)H_{N_2}^{T_b}$ $+ x H_{H_2O}^{T_b} + \frac{(W_2 A_2)(0\,25)(T_C - 298)}{100} + \frac{(W_2 C_2)H_C^{T_C}}{1200}$ $= x H_f^{H_2O} + n_{H_2} H_{H_2}^{T_f} + n_{CO} H_{co}^{T_f} + n_{N_2} H_{N_2}^{T_f} + n_{SiO} H_{sio}^{T_f}$ $+ W_{Fe}(\frac{10.6(T_f - 1873)}{56} + 280) + \frac{W_{Fe} H_f^{Fe_2O_3}}{2}$ $+ W_{Slag}(480 + (0.25)(T_f - 1873)) + W_1 H_{Crack} + \frac{W_3 L_1 H_f^{Cac}}{10000}$

wustite($Fe_0.95O$) phase by carbon monoxide and hydrogen gases in the upper part. Wustite is partly reduced in the reserve zone by the ascending carbon monoxide and hydrogen gases. The amount of iron produced in the reserve zone would depend upon the following parameters:

1. Reserve zone gas temperature

2. Reserve zone solid temperature.

3. Shaft efficiency.

4.3.2 Thermodynamic consideration

The indirect reduction reactions occuring in the reserve zone may be written as follows:

$$Fe_{0.95}O + CO(g) \rightleftharpoons 0.95Fe + CO_2(g) \tag{4.7}$$

$$Fe_{0.95}O + H_2(g) \rightleftharpoons 0.95Fe + H_2O(g) \tag{4.8}$$
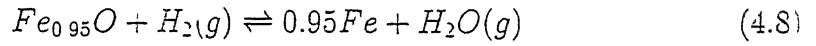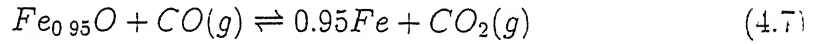
The amount of metallic iron that enters the lower part of the furnace is thus. related to the amount of reducing gases such as carbon monoxide and hydrogen that leave the bosh region. From the thermodynamic analysis we may derive the following:

$$n_{Fe} = \eta \frac{n_{co}}{1 + K_{47}} + \eta \frac{n_{h2}}{1 + K_{48}} \tag{4.9}$$

Where.

$$log K_{47} = (\frac{4300}{4.606(T_{ge} - 50)} - 1.14) \tag{4.10}$$

$$log K_{48} = -(\frac{4350}{4.606(T_{ge} - 50)} + 0.51) \tag{4.11}$$

Reduction of the remaining amount of wustite would occur at high temperatures in the bosh. The reaction mechanism includes the gaseous reduction of

wustite and the carbon gasification reaction i.e.boudouard reaction which is described below:

$$CO_2(g) + C \rightleftharpoons 2CO(g) \qquad (4.12)$$

The direct reduction of wustite in the bosh may be described as follows.

$$Fe_{0.95}O + C \rightleftharpoons 0.95Fe + CO(g) \qquad (4.13)$$

Besides direct reduction of iron ore in the bosh and combustion reactions occuring in the raceway as described in section 4.2. other changes occuring in the lower part of the furnace may be described as below:

1. Carburising of iron phase.

2. Melting of metal phase.

3. Melting of slag phase.

4. Reduction of oxides of nonferrous elements such as silicon, manganese and phosphorus etc.

5. Distribution of sulphur between slag and metal phases.

The lower part is very critical for smooth running of the furnace from heat and chemical point of view. Heat losses through the walls and bottom may be around 80 % of total heat losses from the furnace. Mass and enthalpy balances are used to determine the required fuel rate of the furnace, as a function of the operating parameters such as blast temperature, blast humidity, oxygen enrichment of blast, levels of coal and lime injection through tuyeres etc, as well as assumed parameters such as heat losses, shaft efficiency, temperatures reached by gases and solids in the reserve zone etc. Schematic to show incoming and outgoing species in the lower part is shown in Fig 4.2.
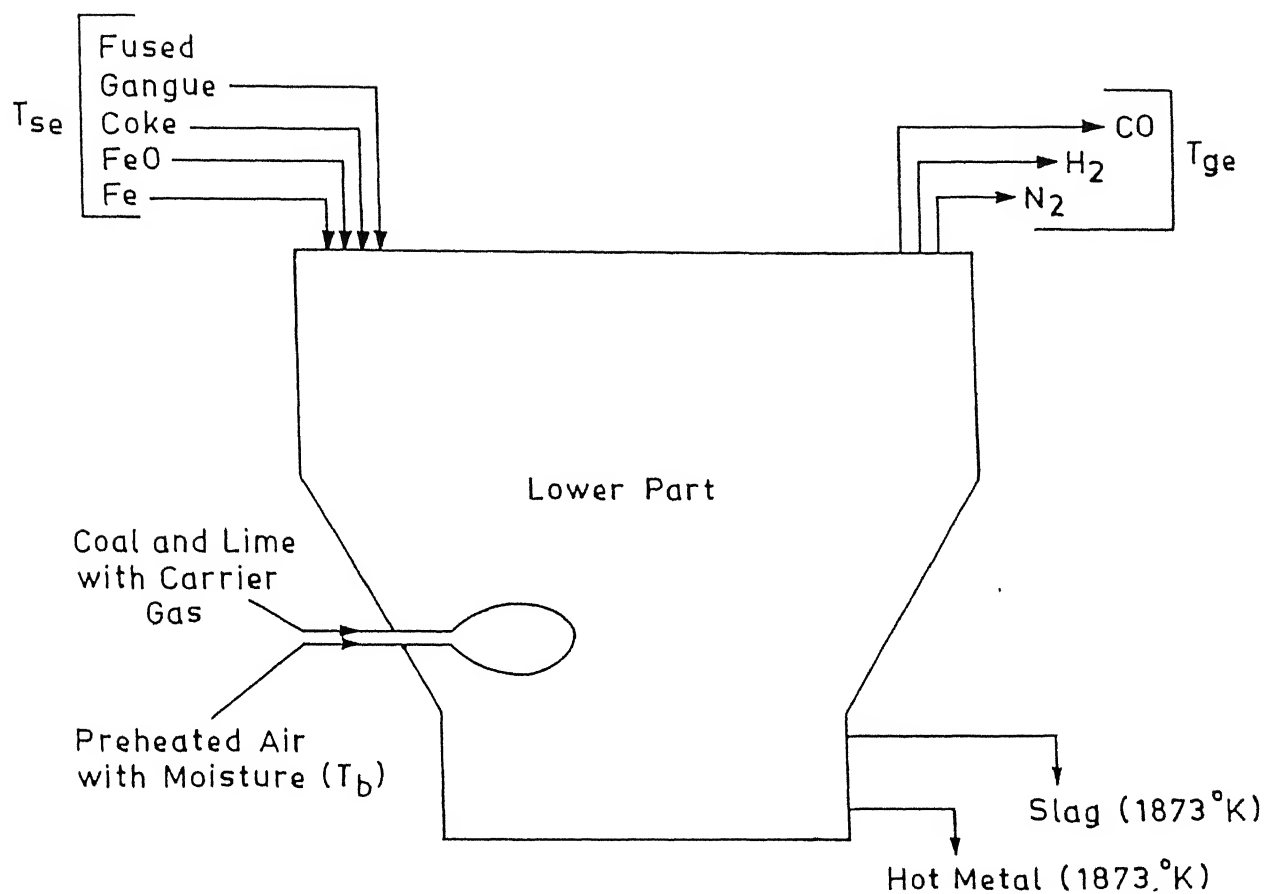
Fig. 4.2. Schematic of Material Flow in the Lower Part of the Furnace.

4.3.3   Heat and Mass balances

To make heat and mass balance in the lower part, it is important to know the gangue to iron weight ratio in the iron bearing materials in the burden and the composition of the gangue. If iron ore and sinter percentage of the burden and their composition are known, one may get the gangue to iron weight ratio as follows·

$$g_r = \frac{\sum e_i \, g_i}{\sum e_i \, f_i} \qquad (4\ 14)$$

Where,

e_i is the percentage of species i in the burden.

g_i the weight fraction of gangue in species i.

f_i is the weight fraction of iron in species i.

Gangue is assumed to consist of silica, alumina, mangnesia and calcium oxides.

The following assumptions are made regarding the composition of hot metal:

1. All P_2O_5 in burden is reduced completely in the bosh to give phosphorous in metal.

2. Partition coefficient of sulphur K_S is fixed using some empirical correlations. It is defined as follows:

$$K_S = \frac{\%S \ in \ slag}{\%S \ in \ Hot \ metal} \qquad (4.15)$$

   Weight fraction of sulphur in slag $= K_S * f_S$

   Where,

   f_S is the weight fraction of sulphur in hot metal.

3. Recovery of manganese, R_{mn} in hot metal may be known by intuition or otherwise. Manganese content of the burden species may not be known

Table 4.3   Equations based on Material and Enthalpy balances in the lower part of blast furnace

S N.	Balancing species	Equation
1.	N_2	$P_1 = \frac{W_1 N_1}{2800} + (1 - O_e) + (W_1 + W_3)R_{cg}$
2.	H_2	$P_2 = \frac{W_1 H_1}{200} + x$
3	O_2	$\frac{P_5 S_1}{6900 \times 2} + 0.5 P_7 = \frac{1.5(W_1 A_1 + W_{2b} A_2)a_2^s}{16 \times 10^6} + \frac{W_1 O_1}{3200} + \frac{W_3 L_1}{10000} + O_e$ $+ 0.5x + 0.5 P_4 + P_6\left(\frac{f_{si}}{28} + \frac{f_{mn}}{110} + \frac{2.5 f_p}{62}\right)$
4.	Fe	$\frac{(0.95)(56)P_5 S_1}{6900} + P_6(1 - f_{si} - f_s - f_{mn} - f_p)$ $= \frac{112(W_1 A_1 + W_{2b} A_2)a_2^s}{16 \times 10^6} + 56(P_8 + 0.95 P_4)$
5.	C	$f_c P_6 + 12 P_7 = \frac{(W_1 C_1 + W_{2b} C_2 + 0.12 W_3 L_1)}{100}$
6.	Slag	$P_5\left(1 - \frac{S_1}{100} - f_s K_s\right) + P_6\left(\frac{60}{28}f_{si} - \frac{71}{55} \times \frac{f_{mn}(1 - R_{mn})}{R_{mn}}\right)$ $= \frac{(W_1 A_1 + W_{2b} A_2)(1 - 0.01 a_2^s)}{100} + 56 g_r(0.95 P_4 + P_8)$
7.	Shaft	$\frac{0.95 P_7 K_{4.7}}{1 + K_{4.7}} + \frac{0.95 p_2 K_{4.8}}{1 + K_{4.8}} = P_8$
8.	Enthalpy	$P_7 H_f^{co} + O_e H_{O2}^{Tb} + (1 - O_e)H_{N2}^{Tb} + x H_{H2O}^{Tb}$ $+ \frac{(W_{2b} A_2)(0.25)(T_{se} - 298)}{100} + \frac{(W_{2b} C_2)H_C^{Tse}}{1200}$ $+ P_8 H_{Fe}^{Tse} + P_4 H_{FeO}^{Tse} + 56 g_r(0.95 P_4 + P_8)H_{ss}(T_{se} - 298)$ $= -x H_f^{H2O} + P_2 H_{H2}^{Tge} + P_7 H_{co}^{Tge} + P_1 H_{N2}^{Tge}$ $+ P_6\left(H_{HM} + \frac{f_{si} H_f^{sio2}}{28} + \frac{f_{mn} H_f^{Mno}}{55} + \frac{f_p H_f^{P2O5}}{62}\right) + \frac{W_3 L_1 H_f^{Cac}}{10000}$ $- P_4 H_f^{FeO} + P_5 H_{ls} + W_1 H_{cr} + 0.8 H_{lo} + \frac{(W_1 A_1 + W_{2b} A_2)a_2^s H_f^{Fe2O3}}{1.6 \times 10^6}$

in most of the cases. MnO content of the slag may be determined by making manganese balance if manganese recovery as defined below is known.

$$R_{mn} = \frac{(W_{mn})_{HM}}{(W_{mn})_{HM} + (W_{mn})_{slag}} \qquad (4.16)$$

$$(W_{mn})_{HM} = f_{mn} \times W_{HM} \qquad (4.17)$$

$$(W_{mno})_{slag} = \frac{71}{55} \times \frac{(1 - R_{mn})}{R_{mn}} \times f_{mn}\, W_{HM} \qquad (4.18)$$

Burden calculations :

Weight of iron per unit weight of burden:

$$f_b = \frac{\sum e_i\, f_i}{100}$$

Weight of burden:

$$W_b = 56 \times \frac{(0\ 95 P_4 + P_8)}{f_b}$$

Weight of iron ore or sinter:

$$W_i = e_i \times \frac{W_b}{100}$$

Model equations based on the heat and mass balance in the lower part of the furnace by taking one mole of dry blast as the basis are summarised in Table 4.3. There are 8 linear equations with 8 unknown variables, unknown variables are W_{2b}, P_1, P_2, P_4, P_5, P_6, P_7, P_8. Equations 3 to 8 of Table 4.3 are solved simultaneously to determine the variables W_{2b} and P_4 to P_8. P_1 and P_2 are determined directly from equations 1 and 2 of Table 4.3. Model equations to determine specific consumption rates of materials per 1000 kg of hot metal are summarised in Table 4.4.

Table 4.4: Calculation of different species per tonne hot metal.

S.N.	Species	Unit	Equation
1.	Coal	Kg	$q_1 = \frac{W_1 \times 10^3}{P_6}$
2.	Coke	Kg	$q_2 = \frac{W_2 b \times 10^3}{P_6}$
3.	Lime	Kg	$q_3 = \frac{W_3 \times 10^3}{P_6}$
4.	Blast	Kmoles	$q_4 = \frac{10^3}{P_6}$
5.	Cast Slag	Kg	$q_5 = \frac{10^3 \times P_5}{P_6}$
6.	Moisture in Blast	Kmoles	$q_6 = \frac{10^3 \times x}{P_6}$
7.	Iron	Kmoles	$q_7 = \frac{10^3 \times (0.95 P_4 + P_8)}{P_6}$
8.	Burden	Kg	$q_8 = \frac{10^3 \times W_b}{P_6}$
9.	Iron ore	Kg	$q_{or} = \frac{10^3 \times W_{or}}{P_6}$
10.	Sinter	Kg	$q_{sn} = \frac{10^3 \times W_{sn}}{P_6}$
11.	Fe_2O_3 in coal	Kmoles	$q_{10} = \frac{q_1 \times A_1 \times a_2^s}{16 \times 10^6}$
12.	Fe_2O_3 in coke	Kmoles	$q_{11} = \frac{q_2 \times A_1 \times a_2^s}{16 \times 10^6}$

4.4 Overall Blast Furnace Modelling:

4.4.1 Introduction

In this section overall blast furnace has been taken as a single entity for consideration. Incoming and outgoing species are shown in Fig 4 3. The model is aimed at finding the temperature and composition of flue gases, that leaves the furnace for comparison and evaluation with actual data. Flue gases consist of carbon monoxide, carbondioxide, hydrogen, water vapour and nitrogen. Model equations are derived by taking one tonne of hot metal as the base. The blast rate, coal injection rate, lime injection rate and amount of burden materials such as coke, ore and sinter have been determined in section 4.3.

4.4.2 Model equations

Oxygen to Iron atom ratio in each burden species may be determined if total iron content as well as FeO content of the species is known.

$$\left(\frac{O}{Fe}\right)_i = 1.5 \times \left(1 - \frac{h_i(56 * 0.95)}{f_i \times 69}\right) + \frac{h_i \times 56}{f_i \times 69} \qquad (4.19)$$

Where,

h_i is the weight fraction of FeO in species i.

Moles of Fe_2O_3 being charged

$$f_1 = \sum \left(f_i - h_i\left(\frac{56 \times 0.95}{69}\right)\right) \times \frac{160}{112} \qquad (4.20)$$

Moles of FeO being charged

$$f_2 = \sum \frac{h_i}{69} \qquad (4.21)$$

Overall oxygen to iron ratio in the burden may be calculated as follows:
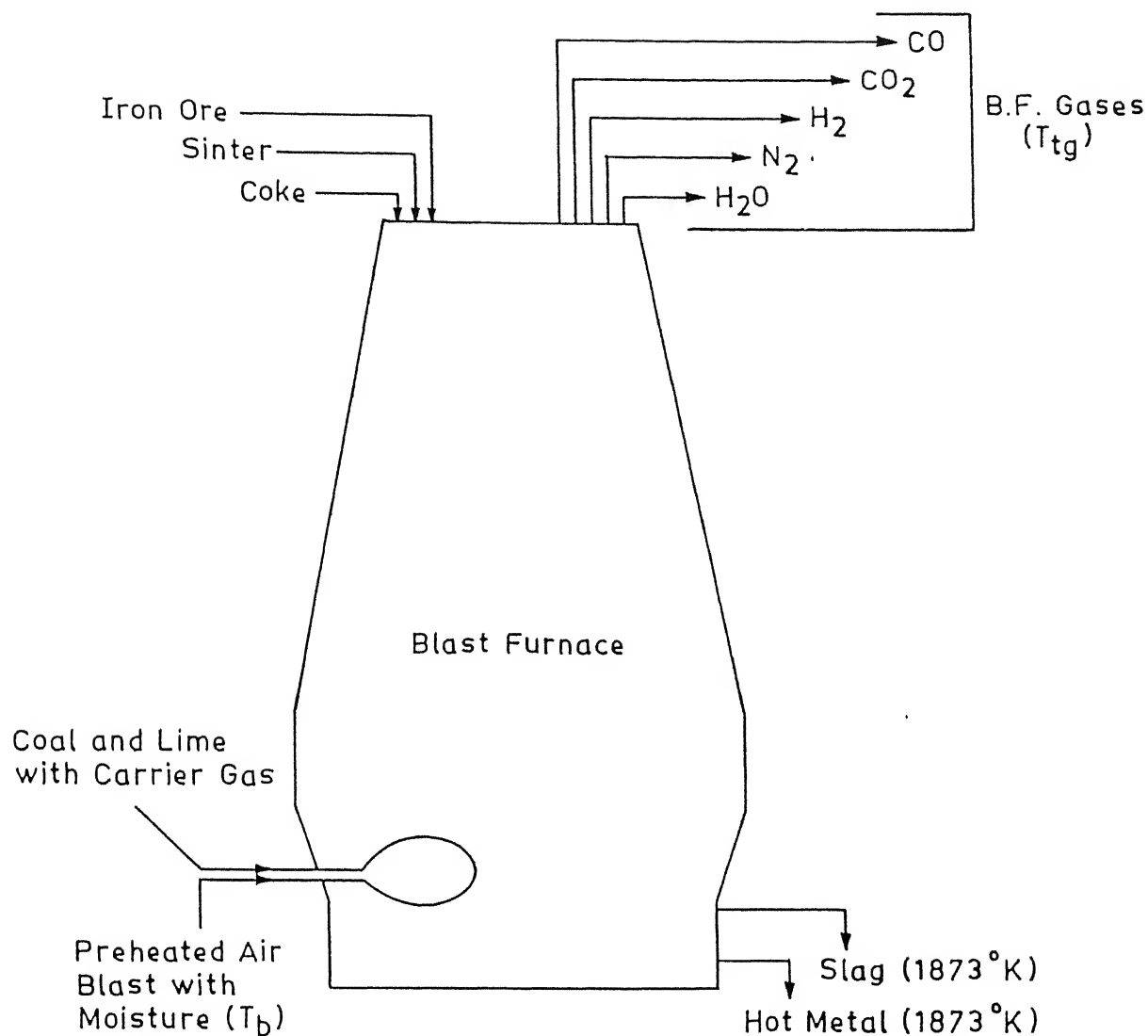
Fig. 4.3. Schematic of Overall Material Flow in the Blast Furnace.

$$\left(\frac{O}{Fe}\right) = \frac{\sum\left(\frac{O}{Fe_i}\right) \times \frac{W_i \times f_i}{56}}{\sum \frac{W_i \times f_i}{56}} \tag{4.22}$$

Carbon balance gives the following:

$$\frac{q_1 C_1}{100} + \frac{q_2 C_2}{100} + \frac{0.12 q_3 L_1}{100} = 12(N_{CO} + N_{CO_2}) + 1000 \times f_C \tag{4.23}$$

Oxygen balance gives the following :

$$\frac{q_1 O_1}{1600} + \frac{3(q_1 A_1 - q_2 A_2)a_2^s}{1.6 \times 10^6} + q_6 + q_8 q_7 + 2q_4 O_e$$
$$-1000 \times \left(\frac{2f_{si}}{28} + \frac{f_{mn}}{55} + \frac{5f_p}{62}\right)$$
$$+ \frac{q_3 L_1 \times 0.02}{100} = N_{CO} + 2N_{CO_2} + N_{H_2O} \tag{4.24}$$

Hydrogen balance gives the following:

$$q_6 + \frac{q_1 H_1}{100} = N_{H_2} + N_{H_2O} \tag{4.25}$$

Relative amount of hydrogen. water vapours, carbon monoxide and carbon dioxide in the gas are influenced by the water gas shift reaction.

$$H_2O(g) + CO(g) \rightleftharpoons CO_2(g) + H_2(g) \tag{4.26}$$
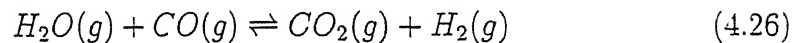
$$\frac{N_{CO_2}}{N_{CO}} = K_{34} \times \frac{N_{H_2O}}{N_{H_2}} \tag{4.27}$$

The reaction being exothermic in nature is favoured at low temperature. However the rate of reaction decreases exponentially with fall in temperature. For all purposes reaction may be ignored at temperature of less than 700K.

There are 3 linear and 1 non linear equation. Which are solved by using a computer programme to determine N_{H_2}, N_{H_2O}, N_{CO} and N_{CO_2}.

Nitrogen balance gives the amount of nitrogen in flue gas.

$$N_{N_2} = \frac{q_1 N_1}{2800} + q_4(1 - O_e) + R_{cg}(q_1 + q_3) \qquad (4.28)$$

Overall heat balance is used to determine the top gas temperature.

$$\begin{aligned}
N_{CO}H_f^{CO} &+ N_{CO2}H_f^{CO_2} + q_4 O_e H_{O_2}^{T_b} + q_4(1 - O_e)H_{N_2}^{T_b} + q_6 H_{H_2O}^{T_b} \\
&= N_{CO}H_{CO}^{T_{tg}} + N_{CO_2}H_{CO_2}^{T_{tg}} + N_{H_2}H_{H_2}^{T_{tg}} + N_{N_2}H_{N_2}^{T_{tg}} + N_{H_2O}H^{T_{tg}} \\
&+ q_1 H_{cr} + q_4 H_{lo} + \frac{q_3 L_1 H_f^{Cac}}{1000} + q_5 h_{ls} + 1000 H_{HM} + q_2 M_2 H_{vp}^{H_2O} \\
&- 1000\left(\frac{f_{si}H_f^{SiO_2}}{28} + \frac{f_{mn}H_f^{MnO}}{55} + \frac{f_p H_f^{P_2O_5}}{62}\right) - (q_6 - N_{H_2O})H_f^{H_2O} \\
&- \left(\frac{1000 f_1}{P_6} + q_{11} + q_{10}\right)H_f^{Fe_2O_3} - \left(\frac{1000 f_2}{P_6} - \frac{S_1 \times P_5}{100}\right)H_f^{FeO} \qquad (4.29)
\end{aligned}$$

From heat balance, a cubic equation with one unknown T_{tg} is obtained, which is solved by iteration.

4.5 Fourth Stage of Modelling:

Fluxes are either incorporated in the sinter or added directly to the furnace to form a slag of desired composition and melting range. Liquid metal and slag phases are separated out by gravity in the hearth or in the cast house. The composition of slag formed in the bosh may be different from that of the cast slag because bulk of the ash in coke is released in the raceway region.

Good permeability of the coke bed in the bosh region is very important for smooth running of the furnace. Presence of viscous slag in the grid may affect the flow of ascending gases through the voids in the coke particles, and this in turn affects adversely the blast furnace productivity. Model equations are derived in this section to find the composition of slag formed in the upper part and lower part of the bosh. These slags have been called stack slag and bosh slag respectively in the present work for simplicity.

Table 4 5: Equations to determine the amounts and composition of slag in different parts of the furnace

S.N	Balancing species	Equation
	Cast slag	
1.	SiO_2	$C_1^s = \dfrac{qor \times or_1 + q_{sn} \times sn_1 + \frac{(q_1 A_1 + q_2 A_2) a_1^s}{100}}{100} - \dfrac{f_{s1} \times 6 \times 10^4}{28}$
2.	CaO	$C_2^s = \dfrac{qor \times or_2 + q_{sn} \times sn_2}{100}$
3.	MgO	$C_3^s = \dfrac{qor \times or_3 + q_{sn} \times sn_3}{100}$
4.	Al_2O_3	$C_4^s = \dfrac{(qor \times or_4 + q_{sn} \times sn_4 + (q_1 A_1 + q_2 A_2) \times \frac{a_3^s}{100})}{100}$
5.	MnO	$C_5^s = \dfrac{(1 - R_{mn})}{R_{mn}} \times f_{mn} \times 1.29 \times 100$
6.	Total Amount	$q_{12} = (C_1^s + C_2^s + C_3^s + C_4^s + C_5^s) \times \dfrac{1}{(1 - \frac{S_1}{100} - f_s \times K_s)}$
7.	Basicity	$q_{13} = \dfrac{(C_2^s + C_3^s)}{C_1^s}$
	Raceway slag	
8.	SiO_2	$R_1 = (q_1 A_1 + \frac{W_2 A_2 \times 10^3}{P_6}) \times \frac{a_1^s}{10^4} + \frac{q_3 L_2}{100}$
9.	CaO	$R_2 = \frac{q_3 \times L_3}{100}$
10.	MgO	$R_3 = \frac{q_3 \times L_4}{100}$
11.	Al_2O_3	$R_4 = (q_1 A_1 + \frac{W_2 A_2 \times 10^3}{P_6}) \times \frac{a_3^s}{10^4} + \frac{q_3 L_5}{100}$
12.	Total Amount	$q_{14} = (R_1 + R_2 + R_3 + R_4)$
	Bosh Slag	
13.	SiO_2	$B_1 = C_1^s - R_1 + \frac{f_{s1} \times 6 \times 10^4}{28}$
14.	CaO	$B_2 = C_2^s - R_2$
15.	MgO	$B_3 = C_3^s - R_3$
16.	Al_2O_3	$B_4 = C_4^s - R_4$

S.N.	Balancing species	Equation
17.	MnO	$B_5 = C_5^s + \frac{f_{mn} \times 71 \times 10^3}{55}$
18.	Total Amount	$q_{15} = B_1 + B_2 + B_3 + B_4 + B_5$
19.	Basicity	$q_{16} = \frac{(B_2+B_3)}{B_1}$
	Stack Slag	
20.	SiO$_2$	$X_1 = \frac{q_{or} \times or_1 + q_s n \times sn_1}{100} - \frac{q_3 L_2}{100}$
21.	CaO	$X_2 = \frac{q_{or} \times or_2 + q_s n \times sn_2}{100} - \frac{q_3 L_3}{100}$
22.	MgO	$X_3 = \frac{q_{or} \times or_3 + q_s n \times sn_3}{100} - \frac{q_3 L_4}{100}$
23.	Al$_2$O$_3$	$X_4 = \frac{q_{or} \times or_4 + q_s n \times sn_4}{100} - \frac{q_3 L_5}{100}$
24.	Total Amount	$q_{17} = X_1 + X_2 + X_3 + X_4$
25.	Basicity	$q_{18} = \frac{(X_2+X_3)}{X_1}$

Stack slag may comprise of constituents present as gangue in the ore, sinter and raw fluxes. Coke particles remain more or less intact. In the bosh region. a part of carbon in coke is consumed via the boudouard reaction. Ash associated with carbon in the coke is added to the stack slag to form the bosh slag.

Transfer of silicon and manganese to metal are assumed to be occuring in the vicinity of the raceway in the hearth region. Composition of the bosh slag, thus, would not be much influenced by the composition of the hot metal. If lime is injected through the tuyeres, corresponding amount of fluxes in the burden must be removed so that final slag composition remains more or less unchanged Model equations to determine the amount and composition of slag in the stack, bosh and hearth region of the furnace are summarised in Table 4.5

Chapter 5

MODEL RESULTS

The model equations derived in the present work have been solved by developing a computer programme. Results of computer calculations are reported in this chapter.

5.1 Raceway Model

Two models described in section 4.2.4 and 4.2.5 for the raceway region were tested against each other as follows:

1. For fixed humidity of the blast, the adiabatic flame temperature was determined by using model equations in section 4.2.4.

2. By assuming the adiabatic flame temperature same as the value computed above, the required humidity is recalculated by using model equation in section 4.2.2 and compared with assumed humidity in step 1. Any discrepancy could be attributed to error, either in model equations or in the computer programme and was sorted out before proceeding further. In the present work, model equations and computer programme were used for different sets of blast temperature, blast humidity and oxygen enrichment of the blast.

Computed flame temperatures are plotted against blast temperature at fixed blast humidity and oxygen enrichment in Fig 5.1. Computed results are plotted against blast humidity in Fig 5 2 for different levels of coal injection. Results depend upon whether presence of ash in coke is taken into account or not and are influenced by the assumed weight fraction of silica in ash that is gasified. The presence of ash in coke has been ignored by many investigators. The empirical relationships as reported by Wegmann[30] and by Chung et al.[31] are as follows:

$$T_F = \frac{(0.9341T_B + 8208W - H(2402 - 1.2177T_B) + 94\ 76)}{(1 + W + 2H)} \tag{5.1}$$

and

$$T_F = 1559 + 0.839T_B - 6.033W_B + 82.87 \times \frac{O_2}{V_B} - 0.031 \times (\frac{16666R_{PC}}{VB})^2 \tag{5.2}$$

where ,

T_F = Raceway adiabatic flame temperature ^oC

T_B = Hot blast temperature ^oC

W = Oxygen in blast(Nm^3/Nm^3 of dry blast)

H = Humidity in blast(Nm^3/Nm^3 of dry blast)

R_{PC} = Pulverised Coal injection ratio(T/W)

V_B = Wind Rate(Nm^3/min)

O_2 =oxygen enrichment(Nm^3/w)

W_B =moisture in Blast(g/Nm^3)

Computed values by using these relationships are plotted in Fig 5.1 for comparison with the results of the model calculations in the present work.
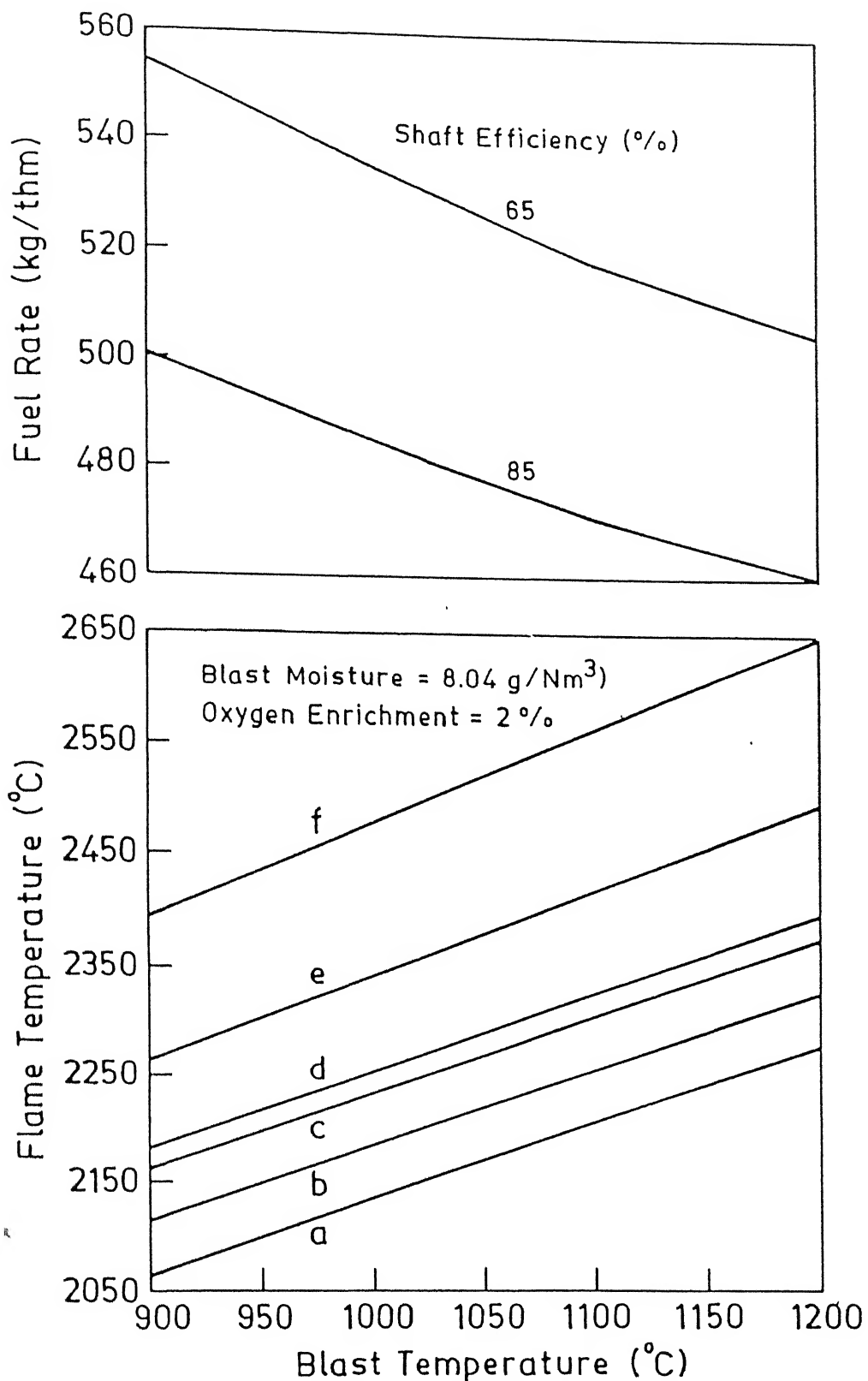
Fig. 5.1. Fuel Rate and Flame Temperature versus Blast Temperature.

a. Present Model with Ash (f = 1.0)
b.   ,,   ,,   ,,   (f = 0.5)
c.   ,,   ,,   ,,   (f = 0.0)
d.   ,,   ,,   without Ash
e. Wegmann's Model
f. Chung et al. Model
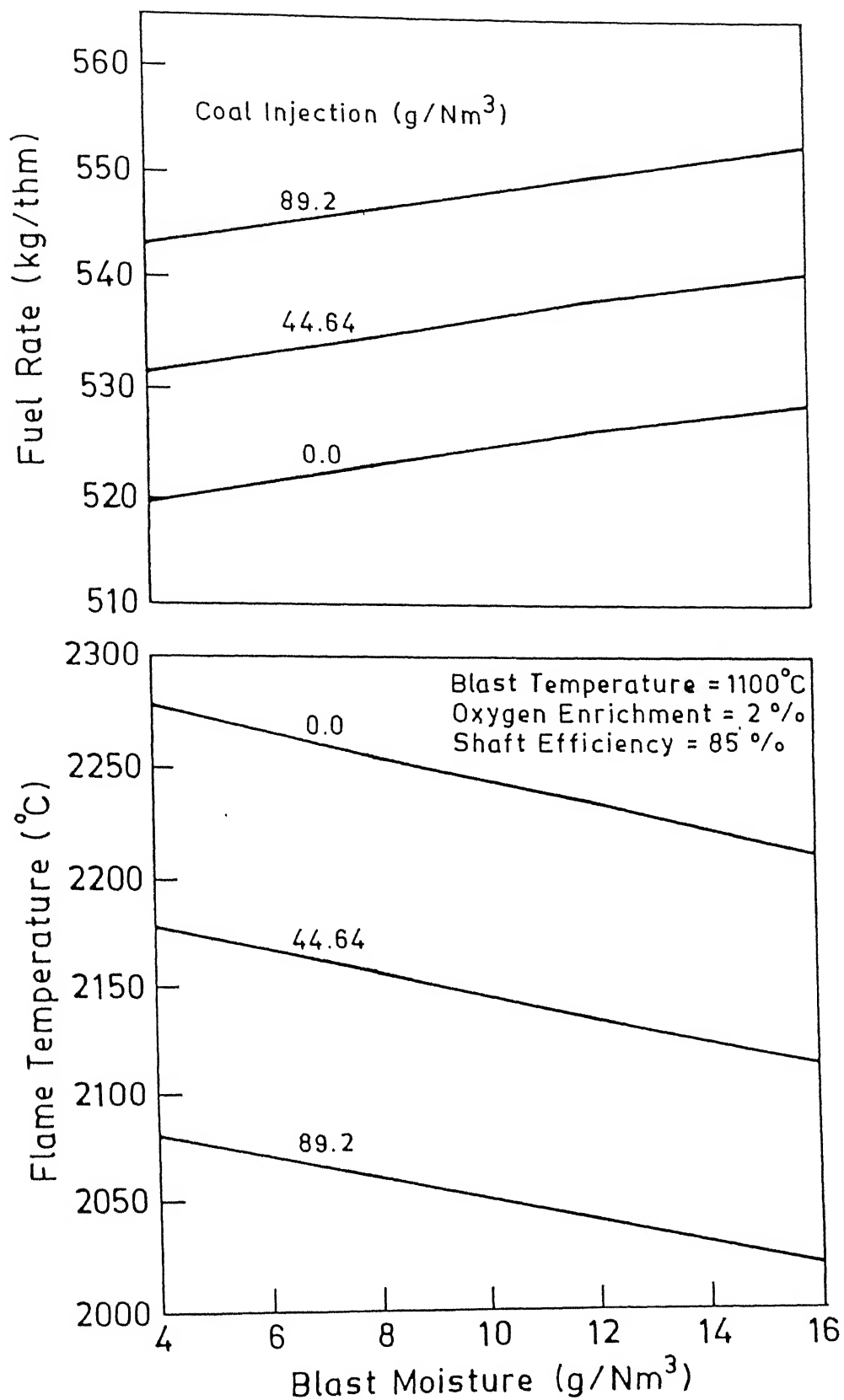
Fig. 5.2. Fuel Rate and Flame Temperature versus Blast Moisture.

Table 5.1· Comparison of computed flame temperature values

Parameter	Unit	Case 1	Case 2
Blast Temperature	^oK	1300	1300
Blast Moisture	(g/Nm^3)	7.21	7.21
Oxygen enrichment	%	2.3	2.3
Computed Flame Temperature	^oK		
Present Model (Without Ash)	^oK	2563	2165
Wagmann's[30] Model	^oK	2653	-
Chung's[31] Model	^oK	2799	2489
Reported value Davenport[32]	^oK	2590	2200

Empirical correlations used by investigators, in general, give higher values of the flame temperature, than the value computed from the model equations based on heat and mass balance in the raceway region.

Davenport[32] determined the flame temperature for two sets of data by making material and enthalpy balances. The data and results obtained by him are summarised in Table 5.1 and they compare well with calculated values using the present model.

Effects of changing the operating parameters such as blast temperature, blast humidity, oxygen enrichment and coal injection rate etc. on the calculation of the adiabatic flame temperature based on the model equations are however, of same order as determined from the empirical correlations. Results of finding the coefficient of these parameters are summarised in Table 5.2.

5.2 Lower zone mathematical model

As explained before, the model aims at finding the fuel rate of the furnace to meet the heat demand of the furnace based on certain assumptions. For given flame temperature, moisture content of the blast is determined using the raceway model. Model equations in the lower zone are solved simultaneously using the computer programme to obtain coke rate, slag rate and burden rate etc. Computed moisture in the blast and fuel rate are plotted against blast temperature at fixed flame temperatures and for two levels of oxygen enrichment of the blast of 2 % and 4 % in Fig.5.3. Results of the model calculations to find the fuel rate as a function of blast temperature for fixed moisture content in the blast are plotted in Fig 5.1, for shaft efficiencies of 0.65 and 0.85. The flame temperature is not affected by the shaft efficiency.

Computed effects of individual parameters such as blast temperature, blast humidity, oxygen enrichment, coal injection, lime injection, hot metal composition etc. on the determination of the fuel rate are summarised in Table 5.3. Computed results of fuel rate and flame temperature determination are

Table 5.2: Comparison to show effect of various parameters on Flame temperature calculations

Parameter	Unit	Present Model	Wegmann [30]	Jin Kyung Chung[31]
Blast Temperature	$+100^{\circ}C$	71.0 - 72.0	76.3	83.9
Blast Moisture	$+1g/Nm^3$	-(5.4 - 5.5)	-(3.5 - 3.6)	-(6.0 - 6.05)
Oxygen enrichment	$+1\%$	43.0 - 44.0	47.5 - 49.0	63.5 - 67.2
Coal injection	$1g/Nm^3$	-(1.84 - 1.9)	–	-(5.5)
Ash in Coke	$+1\%$			
Degree of silica gasification (f=0.0).		-(1.8 - 1.86)	–	–
(f=0.5)		-(6.65 - 6.75)	–	–
(f=1.0)		-(11.7 - 11.85)	–	–
Lime injection	$1g/Nm^3$			
LOI = 0.0		-(1.15)		
LOI = 10.0		-(1.49 - 1.51)		
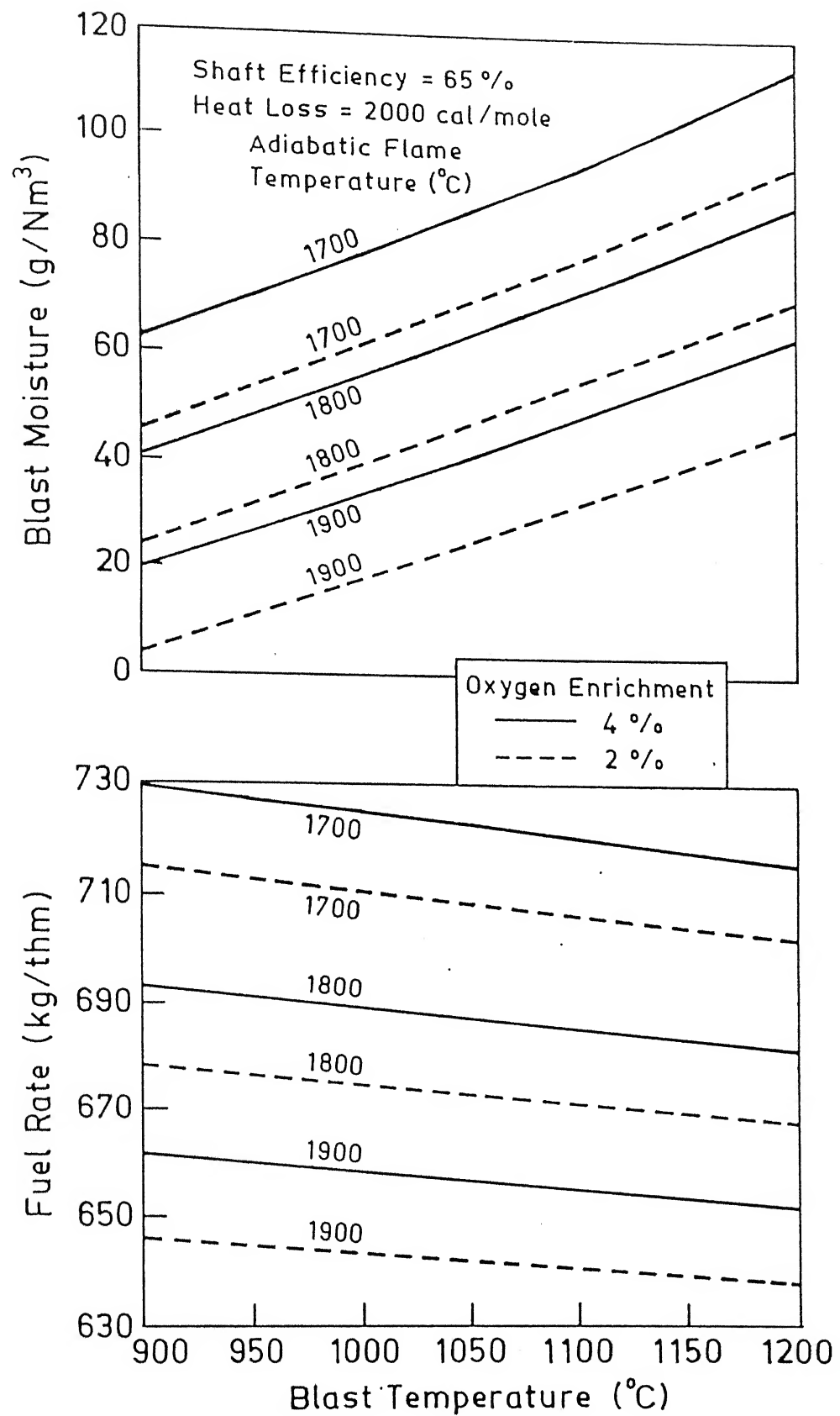
Fig. 5.3. Blast Moisture and Fuel Rate versus Blast Temperature.

Table 5.3: Effects of individual parameters on fuel rate Determination.

Parameter	Unit	Range	Fuel Rate (kg/thm)
Blast Humidity	+1 g/Nm^3	4 - 16	(1.5 - 1.56)
Blast Temperature	+1°C	900 - 1200	-(0 18 - 0.22)
Oxygen enrichment	1%	0.0 - 3.0	-(3.5 - 4.5)
Reserve zone Temperature	+1°C	850 - 1000	(0.39 - 0.41)
Heat Losses	0.1(Gcal/thm)	0.06 - 0.17	28.6 - 35.9
Shaft efficiency	1%	65 - 95	-(2.8 - 3.5)
Coal injection	1(kg/thm)	61.5 - 163.0	0.282 - 0.284
Hot metal [Si]	0.1%	0.65 - 0.95	2.51 - 2.53
Hot metal [Mn]	0.1%	0.1 - 0.25	0.32 - 0 38
Hot metal [P]	0.1%	0.1 - 0.4	1.92 - 1.96
Ash in coke	1%	10 - 19	0.68 - 0.7
Slag Rate	+1(kg/thm)	231 - 307	-(0.14)
Lime Rate LOI = 0.0 LOI = 10.0	+1(kg/thm)	0.0 - 26	 0.09 0.18 - 0.19

plotted against lime to coal weight ratio at different values of LOI in Fig 5.4.

5.3   Overall heat and mass balance

Model equations were used to test the blast furnace data taken from the literature. The operating data for Kimitsu, Taranto, SSAB Lulea and Tata blast furnaces are summarised in Table 5.4.

Computed fuel rate and gas utilisation coefficient (η_{CO}) are plotted against shaft efficiency at different heat losses for each blast furnace in Figures 5.5 to 5.8. Gas utilisation coefficient (η_{CO}) have been determined from the computed top gas analysis as follows:

$$\eta_{CO} = \frac{\%CO_2}{(\%CO + \%CO_2)} \tag{5.3}$$

In general fuel rate decreases with an increase in shaft efficiency and increases with an increase in heat losses from the furnace. Heat losses for the furnace may be 2 % to 5 % of heat demand, which is equivalent to 0.05 to 0.14 Gcal/thm or 1000-2000 Kcal/Kmole of blast. From the plots of the fuel rate versus shaft efficiency, one may determine the actual shaft efficiency for a particular plant corresponding to the reported fuel rate. This in turn allows determination of the CO utilisation in the shaft. Results are summarised in Table 5.5.

5.4   Fourth Stage of Modelling

It is an extension of modelling of second stage, it is aimed at finding the amount and composition of slag formed in different regions of the blast furnace. The slag formed in the stack will consists mainly of the gangue present in the ore, sinter and flux. Ash in the coke remains more or less intact and it does not
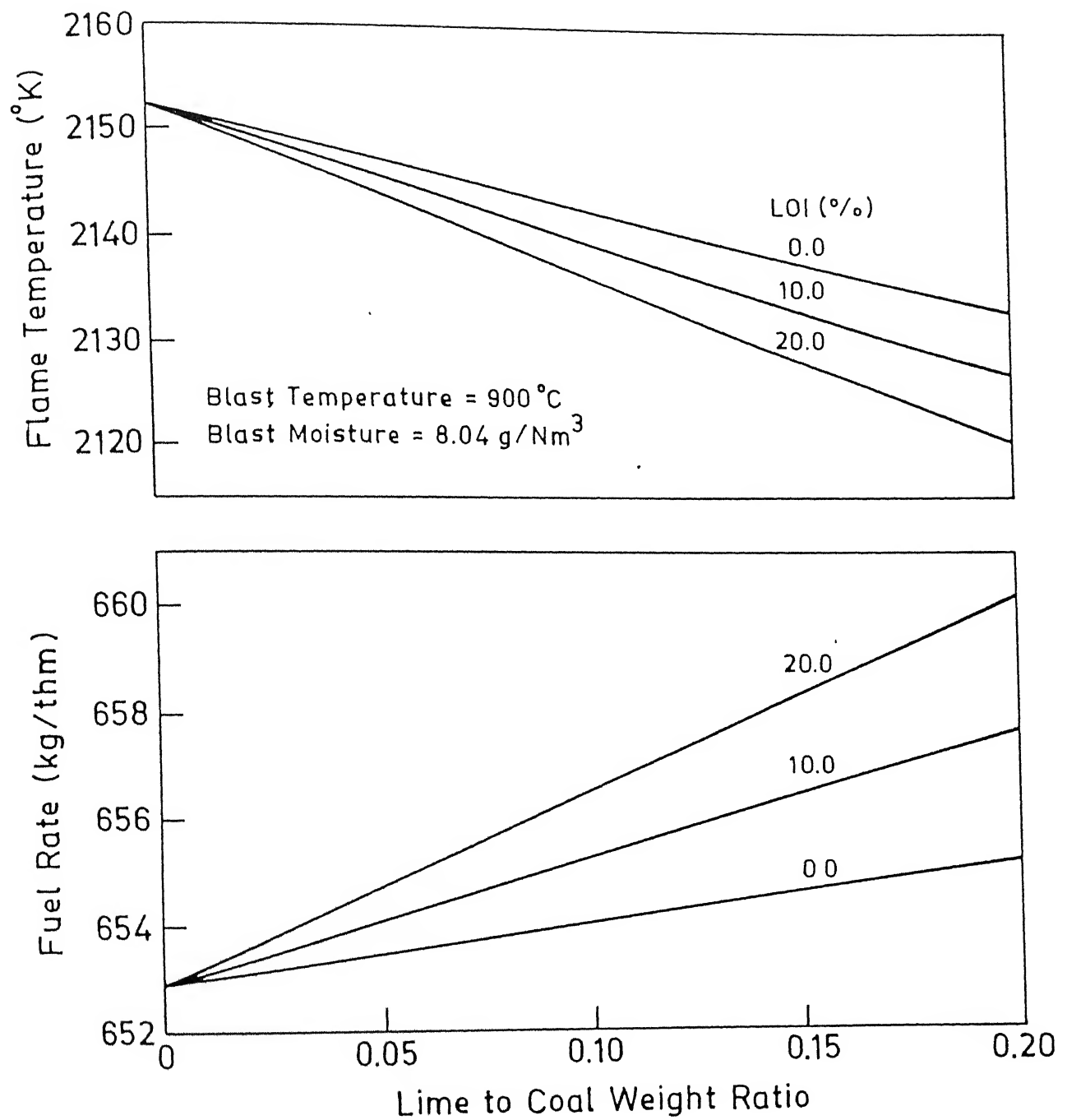
Fig. 5.4. Flame Temperature and Fuel Rate versus Lime to Coal Weight Ratio.

Table 5.4: Data of the different plants

Parameter	Units	Kimitsu Japan[33][34][35]	Taranto Italy[18][36]	SSAB Lulea Germany[8]	TATA India[19]
Blast parameters					
Blast Temperature	$^\circ C$	1208	1165	1123	1130
Oxygen enrichment	%	1.28	4.41	0.0	3.04
Blast Humidity	g/Nm^3	41	9.5	16.4	67.12
Coke Data					
Coke Rate	Kg/t	372	317	464	486
Ash in coke	(%)	11.6	9.77	8.9	18.7
Fe_2O_3 in coke ash	(%)	5.1	8.0	8.0	10.0
Al_2O_3 in coke ash	(%)	27.7	28.0	28.0	30.0
SiO_2 in coke ash	(%)	63.7	64.0	64.0	60.0
Moisture in coke ash	(%)	4.0	4.0	4.1	4.0
Coal/Fuel Data					
Coal Rate	Kg/t	125	183.2	0.0	124
Ash in coal	(%)	10.4	9.12	7.7	16.48
Fe_2O_3 in coal ash	(%)	8.0	8.0	8.0	10.0
Al_2O_3 in coal ash	(%)	27.7	28.0	28.0	30.0
SiO_2 in coal ash	(%)	63.7	64.0	64.0	60.0
Oxygen in coal	(%)	8.5	5.2	8.5	5.3
Nitrogen in coal	(%)	1.9	2.08	1.9	1.62
Hydrogen in coal	(%)	4.7	3.23	4.7	3.9
Carbon in coal	(%)	74.1	80.4	76.8	71.8

Parameter	Units	Kimitsu Japan[33][34][35]	Taranto Italy[18][36]	SSAB Lulea Germany[8]	TATA India[19]
Sulphur in coal	(%)	0.5	1.04	0.5	0.38
Raw Material Data					
Ore in Burden	%	50	50	50	33.45
Ore Analysis					
SiO_2 in ore	(%)	2.88			1.13
CaO in ore	(%)	–			0.0
MgO in ore	(%)	–			0.0
Al_2O_3 in ore	(%)	2.078			1.49
Fe in ore	(%)	63.75			67.15
Sinter Analysis					
$SiO-2$ in sinter	(%)	7.4			
CaO in sinter	(%)	14.1			
MgO in sinter	(%)	4.4			
Al_2O_3 in sinter	(%)	1.1			
FeO in sinter	(%)	7.7			
Fe in sinter	(%)	50.0			
Hot metal Composition					
C	%			4.67	4.13
Si	%			0.27	0.74
Mn	%			0.38	0.04
P	%			0.037	0.202
S	%			0.051	0.058
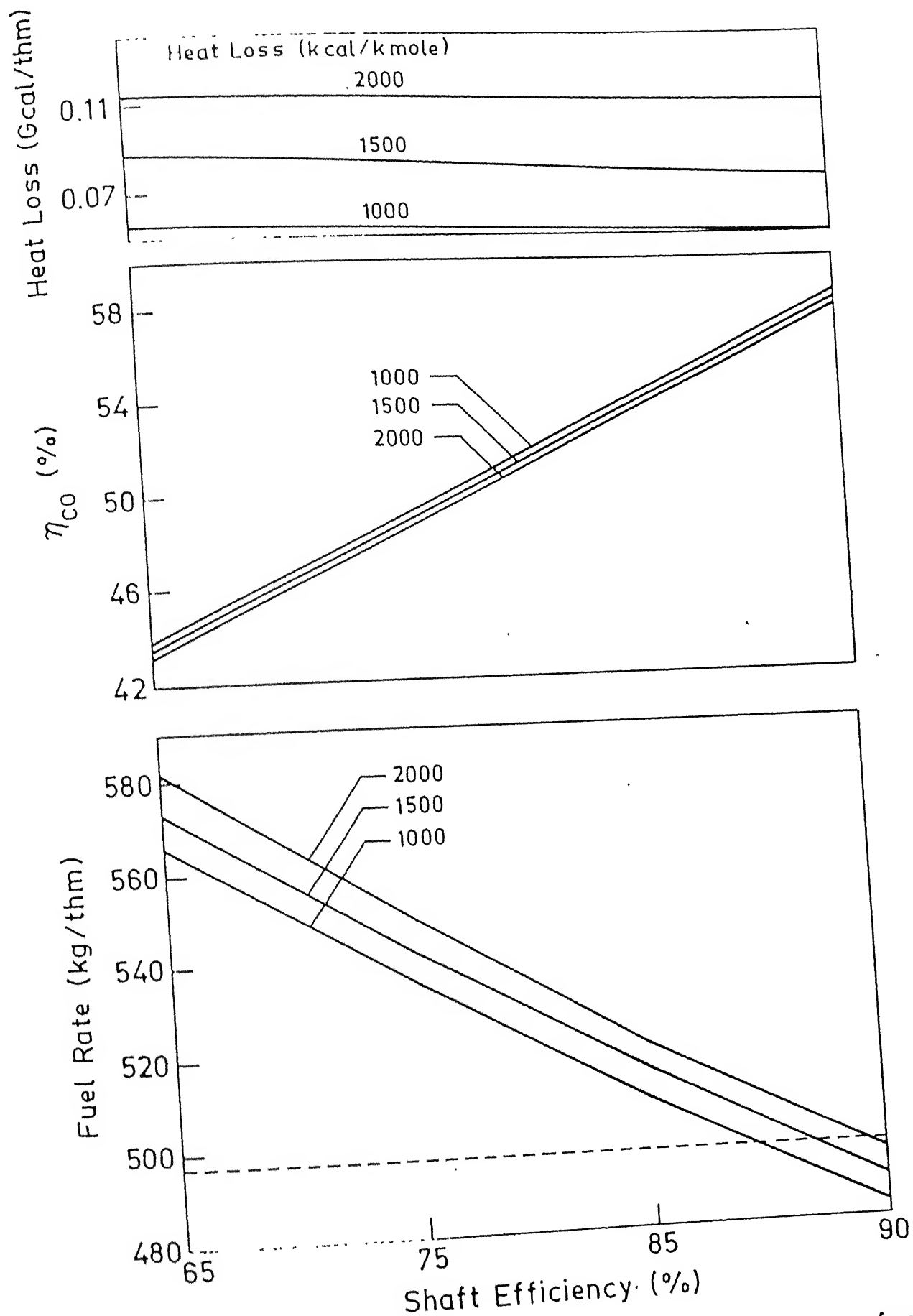
Fig. 5.5. η_{CO} and Fuel Rate versus Shaft Efficiency for Kimitsu No. 4 Blast Furnace of Nippon Steel Corporation.
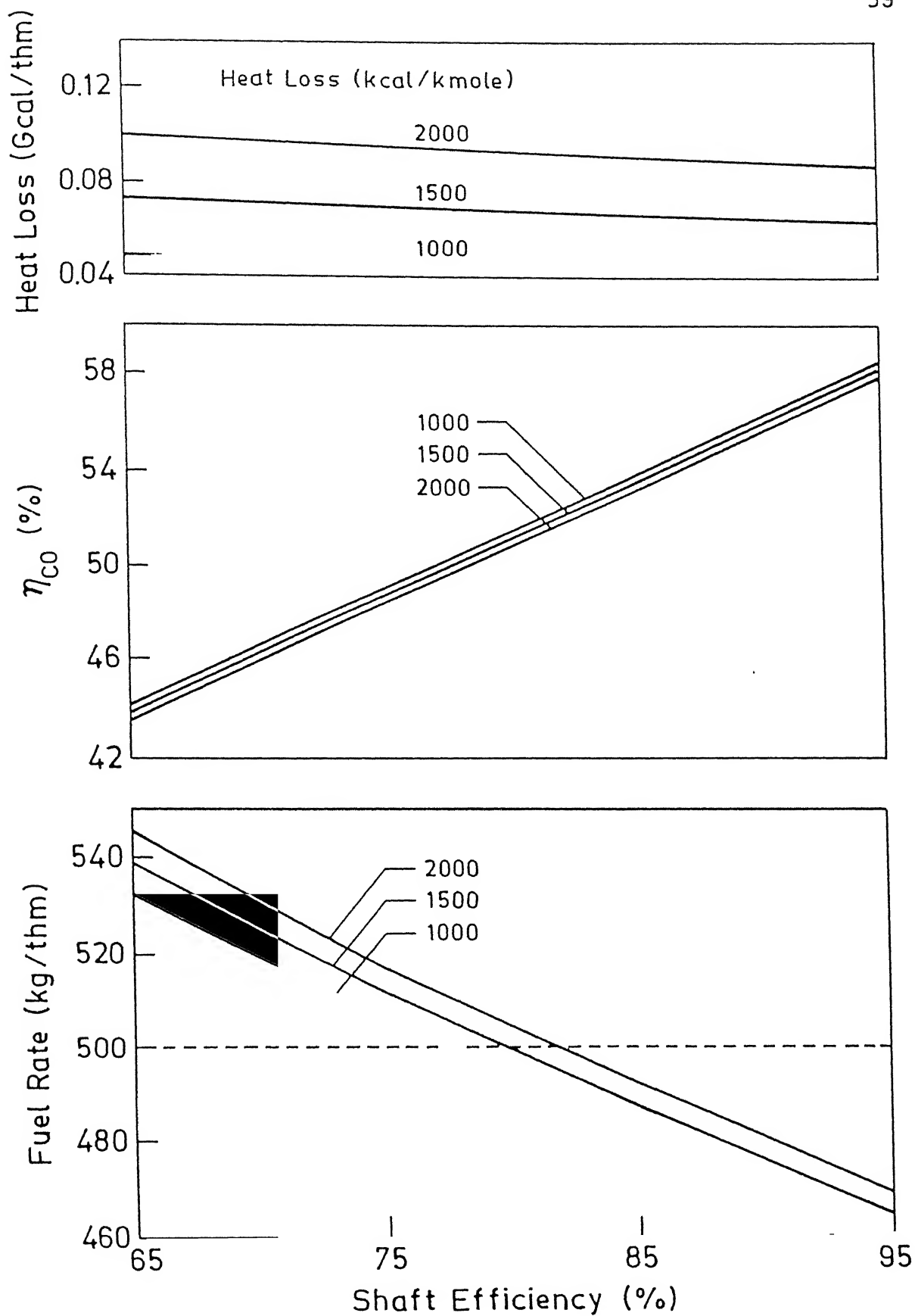
Fig. 5.6. η_{CO} and Fuel Rate versus Shaft Efficiency for Blast Furnace No. 2 of ILVA, Taranto.
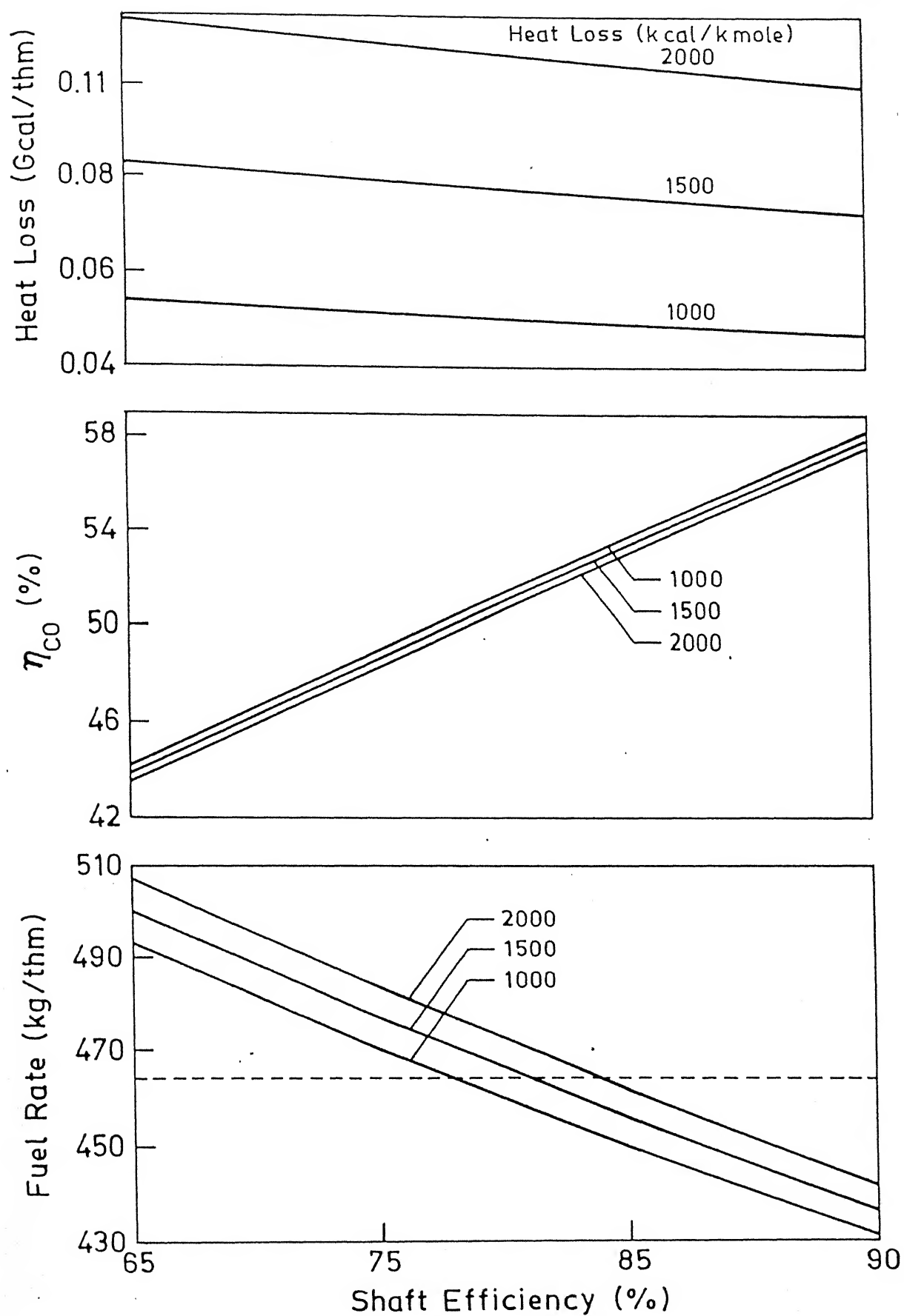
Fig. 5.7. η_{CO} and Fuel Rate versus Shaft Efficiency for Blast Furnace No. 2 of SSAB Lulea.
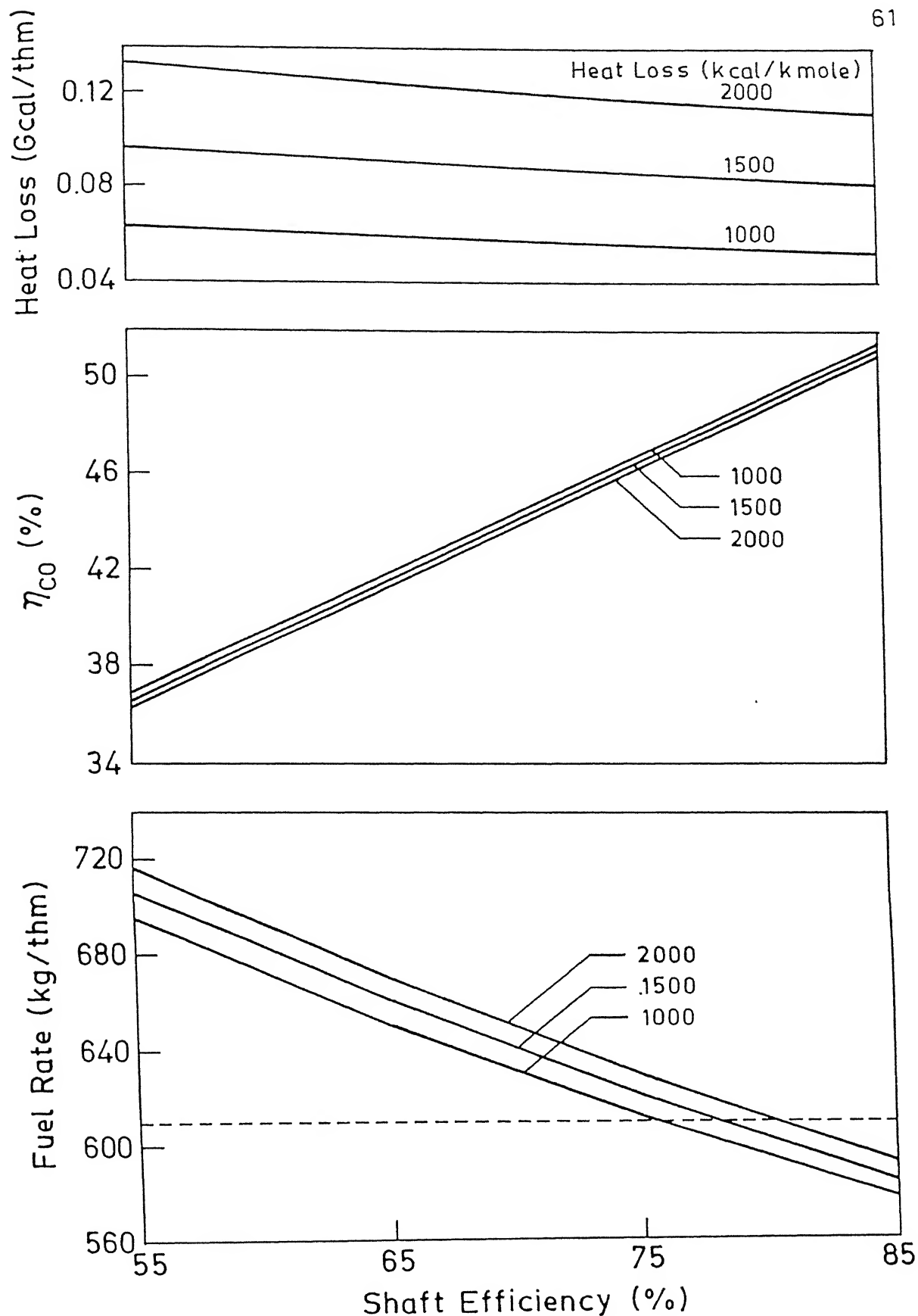
Fig. 5.8. η_{CO} and Fuel Rate versus Shaft Efficiency for G Blast Furnace of Tata Steel.

Table 5.5: Summary of the determination of Shaft Efficiencies

Plant	Fuel Rate (kg/thm)	Assumed Heat Loss		Shaft efficiency (%)	Computed η_{CO}(%)
		(Cal/mole)	(Gcal/thm)		
Kimitsu[33]	497	1000	0.05	89.4	55.8
		1500	0.076	92	56.6
		2000	0.11	94	57.5
Taranto[18]	500.2	1000	0.045	77	50.0
		1500	0.069	79.6	51.0
		2000	0.092	81.8	51.6
SSAB Lulea[8]	464	1000	0.05	77.8	50.2
		1500	0.077	81	51.4
		2000	0.105	83.8	52.3
TISCO[19]	610	1000	0.056	75.6	47.0
		1500	0.085	78	47.8
		2000	0.115	80.4	48.7

contribute to the slag in the stack. In the bosh, a part of carbon in coke is consumed due to the direct reduction of iron ore as well as carburising of iron. Ash associated with the carbon in the coke might join the slag stream in the bosh.

Cast slag comprises of the slag that descends from the bosh, ash that is released due to combustion of coal and coke in the raceway region and lime that is injected along with the coal. A part of silica that is released in the raceway may be gasified to give vapours of silicon monoxide in the tuyere gases.

$$SiO_2 + C \rightleftharpoons SiO(g) + CO(g) \tag{5.4}$$
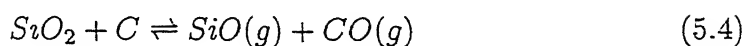
At lower temperatures in the vicinity of raceway, silicon monoxide vapours take part in the gas-metal and gas-slag reaction.

$$SiO(g) + [C] \rightleftharpoons [Si] + CO(g) \tag{5.5}$$

$$SiO(g) + CO(g) \rightleftharpoons (SiO_2) + C \tag{5.6}$$
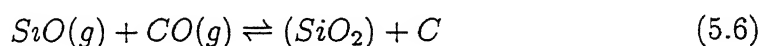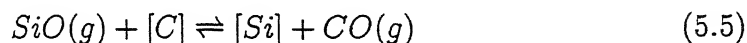
Reduction of silica via slag metal reaction given below is considered to be sluggish and hence ignored.

$$(SiO_2) + 2[C] \rightleftharpoons [Si] + 2CO(g) \tag{5.7}$$

If silica could be reduced by carbon to give silicon in the bosh iron, lime to silica weight ratio in the bosh slag would be increased further. Computed amounts as well as lime to silica weight ratio in the cast slag, bosh slag and stack slag are plotted against lime to coal weight ratio in Fig 5.9. Typical results of computation using 4 stages of model equations are included in Table 5.6.
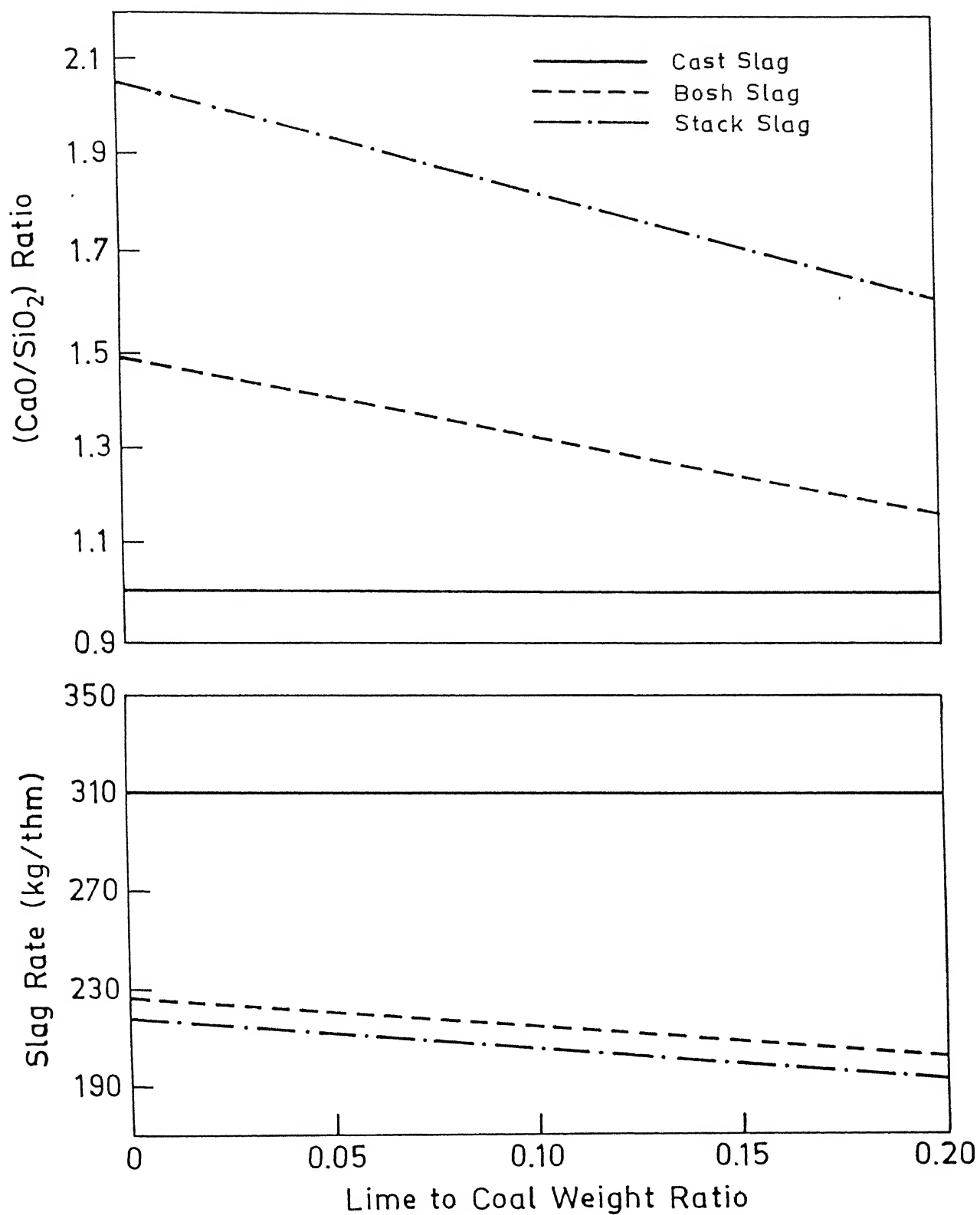
Fig. 5.9. (CaO/SiO_2) Ratio and Slag Rate versus Lime to Coal Weight Ratio.

Table 5.6: Typical Results of computation using 4 stages of model equations.

	1	2	3	4	5
Assumed Values					
RAFT (°K)	2073	2073	2073	2073	2073
Blast Temperature (°C)	900	900	900	900	900
Oxygen Enrichment (%)	2.00	2.00	2.00	2.00	2.00
Reserve zone Temperature (°K)	1123.0	1123.0	1123.0	1123.0	1123.0
Heat Losses (cal/mole)	2000.0	2000.0	2000.0	2000.0	2000.0
Shaft Efficiency (%)	65.0	65.0	65.0	65.0	65.0
Coal Rate (g/mole)	0.00	2.0	2.0	2.0	2.0
Lime to Coal weight ratio	0.00	0.0	0.1	0.15	0.2
Computed Values					
Coal Rate (Kg/thm)	0.00	132.24	132.22	132.21	132.20
Blast Moist (g/Nm3)	58.31	24.12	21.98	20.91	19.83
Coke Rate (Kg/thm)	692.35	546.05	544.39	543.56	542.73
Replacement Ratio	0.00	1.11	1.12	1.13	1.13
Lime Rate Kg/thm	0.00	.00	13.22	19.83	26.44
Fuel Rate Kg/thm	692.35	678.29	676.61	675.77	674.93
Cast Slag Kg/thm	316.39	311.60	311.32	311.18	311.03
Stack Slag Kg/thm	217.34	217.74	205.09	198.77	192.44
Bosh Slag Kg/thm	225.20	226.58	214.04	207.77	201.50
Blast Rate Nm3/thm	1592.34	1525.57	1521.40	1519.31	1517.22
Heat Losses(Gcal/thm)	0.14	0.14	0.14	0.14	0.14

Top Gas (Nm3/thm)	2219.50	2172.35	2166.03	2162.86	2159.69
Top Gas Temp. (°C)	321.56	350.29	352.85	354.12	355.40
Heat Demand (Gcal/thm)	2.7816	2.6710	2.6631	2.6592	2.6552
CAST SLAG COMPOSITION					
SiO2 (%)	34.55	34.06	34.03	34.01	34.00
CaO (%)	33.17	33.69	33.73	33.74	33.76
MgO (%)	7.88	8.01	8.02	8.02	8.02
Al2O3(%)	22.72	22.55	22.54	22.54	22.53
S (%)	1.23	1.23	1.23	1.23	1.23
FeO (%)	0.28	0.28	0.28	0.28	0.28
MnO (%)	0.17	0.17	0.17	0.17	0.17
CaO/SiO2	0.96	0.99	0.99	0.99	0.99
(CaO+MgO)/SiO2	1.19	1.22	1.23	1.23	1.23
STACK SLAG COMPOSITION					
SiO2 (%)	23.92	23.92	25.26	25.99	26.76
CaO (%)	49.01	49.01	46.19	44.64	42.99
MgO (%)	11.65	11.65	12.22	12.53	12.86
Al2O3(%)	15.42	15.42	16.34	16.85	17.38
CaO/SiO2	2.05	2.05	1.83	1.72	1.61
(CaO+MgO)/SiO2	2.54	2.54	2.31	2.20	2.09

BOSH SLAG COMPOSITION					
SiO2 (%)	31.32	31.58	33.34	34.30	35.32
CaO (%)	47.30	47.10	44.26	42.71	41.06
MgO (%)	11.24	11.19	11.71	11.98	12.28
Al2O3(%)	18.90	19.02	20.13	20.74	21.38
S (%)	1.73	1.69	1.79	1.84	1.90
FeO (%)	.39	.39	.41	.42	.43
MnO (%)	.82	.81	.86	.89	.92
CaO/SiO2	1.51	1.49	1.33	1.25	1.16
(CaO+MgO)/SiO2	1.87	1.85	1.68	1.59	1.51
TOP GAS COMPOSITION (dry basis)					
CO (%)	26.44	25.48	25.49	25.49	25.50
CO2(%)	17.39	17.27	17.26	17.26	17.25
η_{CO}(%)	39.68	40.39	40.37	40.37	40.36
H2 (%)	4.44	4.29	4.13	4.06	3.98
N2(%)	51.73	52.96	53.11	53.19	53.27

Chapter 6

DISCUSSION

6.1 Effect of blast parameters on performance of blast furnace

Effect of individual operating parameters on the determination of blast humidity for maintaining the constant flame temperature and corresponding effects on the determination of fuel rate are summarised in Table 6.1.

The effect of individual parameters such as blast temperature, blast humidity, oxygen enrichment and coal injection on the flame temperature and fuel rate calculation are summarised in Table 6.2.

The fuel rate decreases with an increase in the flame temperature in all cases but the effect is the maximum when the flame temperature is increased by increasing the blast temperature and the effect is minimum when flame temperature is increased by increasing the oxygen enrichment of the blast.The limit to which the flame temperature could be increased might vary from furnace to furnace depending upon the design of the furnace and nature of raw materials used. Operating the furnace at flame temperature higher than the limiting value for a long time may lead to irregularities such as hanging, burning of tuyeres and hearth break out etc.

Table 6 1: Effect of various parameters on Fuel rate and Blast moisture determination at constant Flame temperature

Parameter	Unit	Range	Blast Moisture (g/Nm³)	Fuel Rate (kg/thm)
Blast Temperature	+1°C	900 - 1200	0.145 - 0.166	-(0.034 - 0.037)
Oxygen enrichment	1%	0.0 - 3.0	8.13	7.5 - 9.0
Reserve zone Temperature	+1°C	850 - 1000	0.0	0.4 - 0.43
Coal injection	1(kg/thm)	66.0 - 166.0	-0.26	-(0.106 - 0.107)
Ash in coke	1%	10 - 19		
(f=0.0)			0.22 - 0.25	0.4 - 0.5
(f=0.5)			1.0 - 1.05	0.88 - 0.9
(f=1.0)			1.7 - 1.75	1.8 - 2.0
Lime Rate	+1(kg/thm)	0.0 - 26		
LOI = 0.0			- 0.14	-(0.13 - 0.14)
LOI = 10.0			- 0.190	-(0.11 - 0.12)

Table 6.2: Effect of blast parameters on Flame temperature and Fuel rate determination

Parameter	Unit	ΔT_f	ΔW_{fuel}	$\frac{\Delta W_{fuel}}{\Delta T_f}$
Blast Temperature	+ 1°C	0.7	-0.21	-0.31
Blast Humidity	+ 1 g/Nm^3	-5.5	1.5	-0.27
Oxygen Enrichment	+ 1 %	43.5	-4.0	-0.1
Coal Injection	+ 1 g/Nm^3	-1.9	0.46	-0.24

Result shows that fuel rate tends to decrease at the rate of around 0 035 kg per unit increase in blast temperature, if humidity is increased simultaneously at the rate of around 15 g/Nm^3 or (0.25 kg/ton) to maintain the same flame temperature. If blast humidity was maintained at same level and flame temperature was allowed to increase, fuel rate would decrease at the rate of 0 21 kg per unit increase in blast temperature. If the flame temperature could be maintained at the constant level by decreasing the oxygen enrichment of blast, at the rate of 0.017 % per unit increase in blast temperature instead of increasing the oxygen enrichment of blast, fuel savings would be the order of 0.133 kg per unit increase in blast temperature. If coal is injected, steam injection must be lowered at the rate of 0.3 kg per kg of coal injected in order to maintain the constant flame temperature. Fuel savings are computed to be around 0.1 kg per kg of coal injected and it gives a replacement ratio of 1.1. If coal injection rate is accompanied by increase of 1.7 °C in blast temperature, to maintain same temperature instead of decreasing the humidity, fuel savings are around 0.16 kg, it gives coke replacement ratio of 1.16. On the other hand, if coal injection is accompanied by increase in oxygen enrichment of 0.03 % of blast for maintaining the flame temperature, fuel rate increases by 0.16 kg, to give a coke replacement ratio of 0.84. These results tend to highlight the fact that the oxygen enrichment should be practised when the maximum limit of increasing the blast temperature and decreasing the blast humidity have been reached. If coal injection beyond the limiting conditions is not accompanied by oxygen enrichment of blast, there will be fall in the flame temperature. It may lead to chilling of hearth, incomplete combustion of coal particles and non dissolution of lime particles which ,in turn, would make it difficult for smooth working of the furnace. Oxygen enrichment helps to reduce the amount of gases produced in the raceway and bosh region and it will have beneficial effects on the furnace productivity. Specific consumption rates of the blast for two cases are compared below in Table 6.3. Higher proportion of oxygen in the blast would also favour complete combustion of coal particles in the raceway as mentioned by K. H. peter[16].

Table 6.3: Specific consumption rates of the Blast with oxygen enrichment

Oxygen Enrichment (%)	Blast Rates (Nm^3/ton)	
	Case 1	Case 2
0.0	1612	1612
1.0	1567	1526
2.0	1526	1448
3.0	1437	1377

6.2 Reserve zone temperature

It has no effect on the flame temperature calculations. Reserve zone temperature might be decreased with an increase in the reactivity of coke. Utilisation of CO gas for indirect reduction in the reserve zone increases with a decrease in the reserve zone temperature. Results of model calculations give fuel saving of 0.4 kg/thm per unit decrease in the reserve zone temperature. Hence to get optimum results, coke of high reactivity should be preferred, resulting in lower reserve zone temperature and better utilisation of gases.

6.3 Shaft efficiency

It has got no bearing on the flame temperature calculations. The shaft efficiency is related to attainment of equilibrium for the reduction of wustite by gases such as CO and H2. Fuel rate tends to decrease at the rate of as much as 3 to 4 kg per unit percentage increase in the value of shaft efficiency. In modern large blast furnaces using well prepared burden material, the shaft efficiency may reach 100 % and there may not be much scope for reduction of fuel rate. Presence of hydrogen content in the gases in the bosh region tends to increase the shaft efficiency as hydrogen molecules being smaller diffuse faster into the iron ore than carbon monoxide. Hydrogen content of the gas increases with a increase in steam injection rate and coal injection rate. All efforts are required to improve the reducibility of incoming iron ore and sinter and other iron bearing species in the burden for getting shaft efficiency close to 100 %.

6.4 Heat Losses

Heat losses in Gcal/hr. are estimated empirically as follows:

$$H_{loss} = 1.9 \, d_h$$

where d_h is the diameter of hearth

For large and modern blast furnaces heat losses are estimated to be less than 0 1 Gcal/thm Increase in heat losses by 0 01 Gcal/thm increases the fuel rate by 3 kg/thm, The extent of heat losses may vary from furnace to furnace. Uncertainty regarding heat losses may pose problems in checking the validity of the model.

6.5   Lime injection

If lime is injected without changes in blast parameters such as blast temperature, blast humidity, oxygen enrichment etc., calculations show that fuel rate must increases by 0.09 kg per kg of fully calcined lime and flame temperature decreases at the rate of 1.1 °C per g/Nm^3 of lime in the blast. If lime contains undecomposed carbonates so that loss on ignition becomes 10 %, decrease in flame temperature is 1.5 °C per g/Nm^3 of lime and fuel rate must increase at the rate of 0.18 kg per kg of lime. If lime injection is accompanied by a decrease in humidity or increase in blast temperature so that flame temperature remains unchanged, there may be fuel saving of 0.13 kg per kg and 0.11 kg per kg of lime at 0.0 and 10.0 % LOI in lime respectively. Results are plotted in Fig 6 1. One may conclude that heat balance consideration in raceway and in the lower zone of the furnace are not much affected by injection of lime up to the limit of lime to coal weight ratio of 0.2. It has, however significant effect on the amount and composition of intermediate slags formed in the bosh region. Results of finding the amount and composition of bosh and stack slag have been summarised in Table 5.6. One may estimate the melting point of slag by referring to Al_2O_3 - CaO - SiO_2 ternary diagram[37] which is shown in Fig 6.2. Presence of magnesia in the slag is considered to be equivalent to presence of lime for estimating the melting point using the ternary diagram. The amount and composition of cast slag have been assumed to remain independent of lime to coal weight ratio in the injectant. Estimated melting points of the bosh and stack slag for different lime and coal weight ratios are plotted in Fig 6.3.
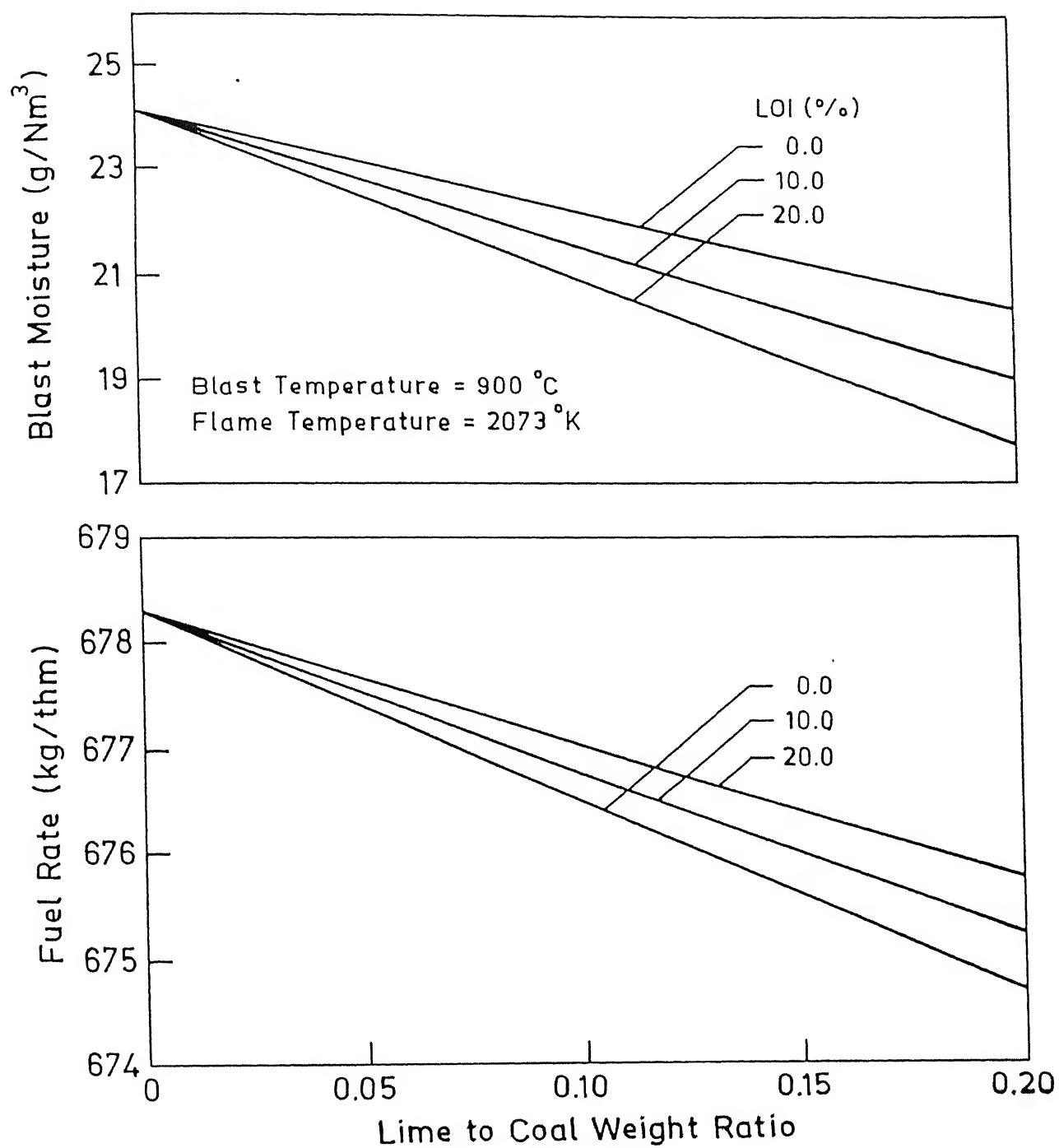
Fig. 6.1. Blast Moisture and Fuel Rate versus Lime to Coal Weight Ratio.
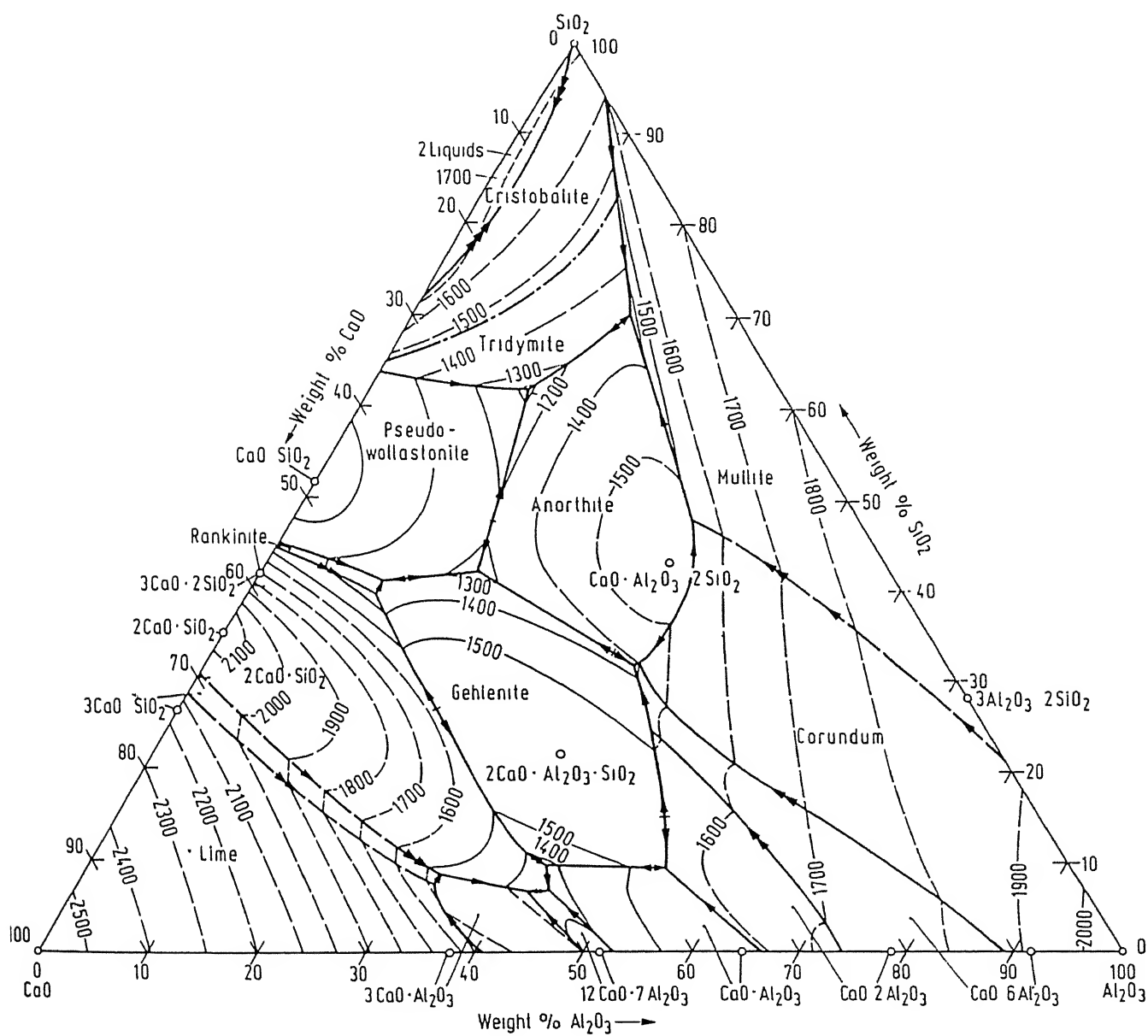
Figure 6.2: Ternary Diagram of Al_2O_3 - CaO - SiO_2
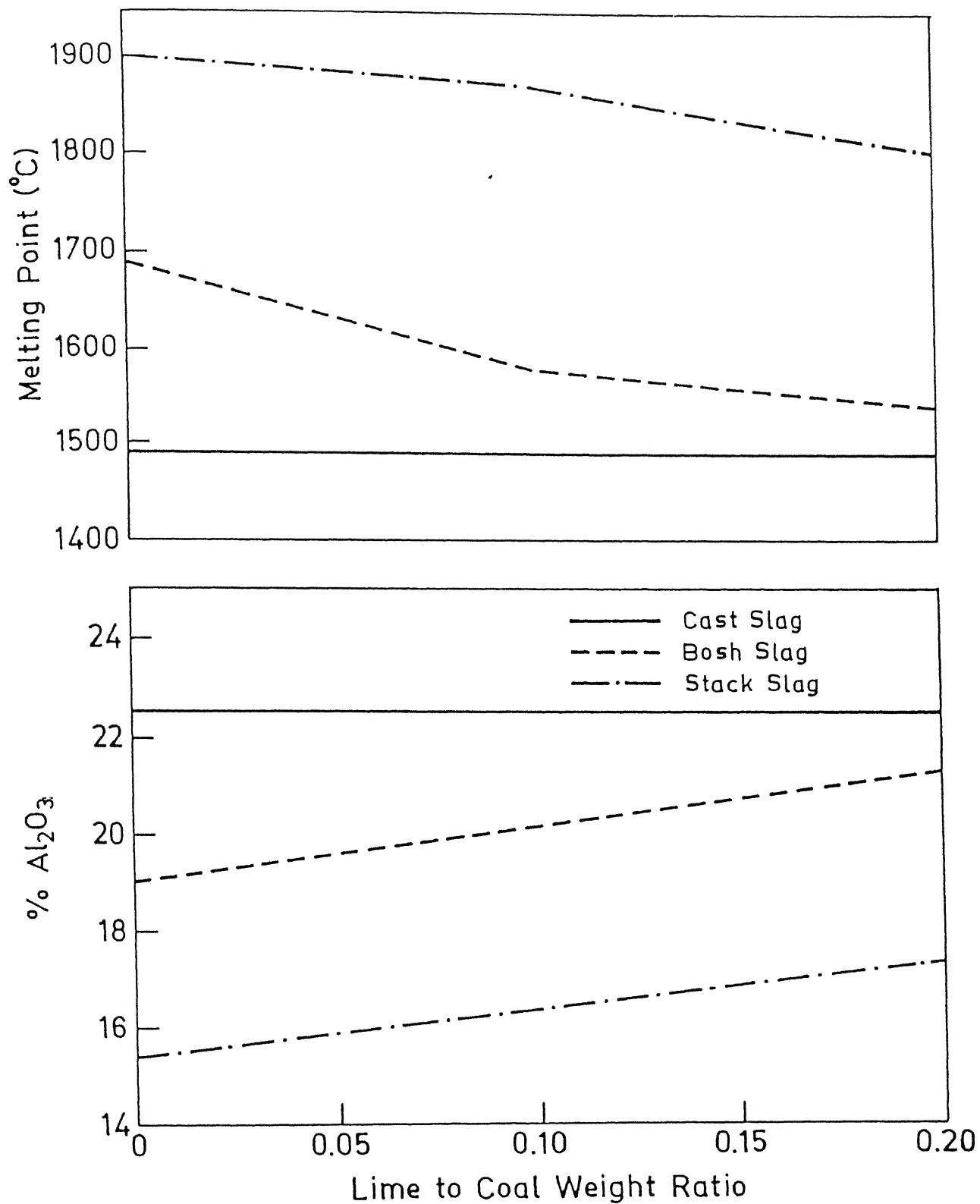
Fig. 6.3. Melting Point and % Al_2O_3 versus Lime to Coal Weight Ratio.

Injection of lime through the tuyeres has beneficial effect of lowering the melting range of the bosh slag and stack slag. Presence of oxides of iron and manganese in the slag may lower the melting range of these slags further. If melting range of the bosh slag and its fluidity are improved by injection of lime, the furnace might accept increased wind rates without running into problems such as flooding etc. The furnace productivity would, thus be enhanced. Reactivity of lime is very important. It refers to the rate at which it becomes part of the liquid slag at any temperature. If lime of poor reactivity is injected, lime particles may not dissolve in the slag and ultimately find their way to the bosh. The permeability of the coke bed would be adversely affected, and capacity of the furnace to accept wind may be retarded at the cost of the productivity. Efforts should be made to operate the furnace at slightly higher flame temperature when lime and coal particles are co-injected through tuyeres. This will ensure complete combustion of coal particles as well as rapid dissolution of the lime. Such conditions favour reduction in coke rate, an increase in the productivity and overall lowering the cost of hot metal. Injection of lime into the raceway could favour the following in addition to heat balance considerations:

1. Lime combines insitu with silica, that is released due to combustion of coal and coke particles in the raceway region. This in turn retards gasification of silica to silicon monoxide. As transfer of silicon to metal is attributed to formation of silicon monoxide, silicon content of metal may decrease with increase in injection of lime through the tuyeres.

2. Injection of lime increases the sulphide capacity of the slag in the vicinity of the raceway region. This will reduce the extent of sulphur pickup by metal phase in the bosh region.

Benefits of lime injection on lowering of silicon and sulphur level in hot metal have been confirmed by Komatsu et al[38]. Results of their findings are summarised in Table 6.4. Scientific and planned plant trials are needed to assess merits of simultaneous injection of coal and lime through the tuyeres of a blast furnace along with the blast under indian conditions. The study must be aimed

Table 6.4: Operational results with flux injection at Kokura No.2 BF[38]

Items	Base Period	Dolomite = 10kg/THM	Dolomite = 15kg/THM
Productivity (T/D)	3581	3554	3567
Coke rate (kg/THM)	464.1	470.5	467.7
PC rate (kg/THM)	23.6	22.9	22.8
Dolomite rate (kg/THM)	0.0	9.0	13.5
Blast temperature ($^{\circ}$C)	1178	1173	1181
Blast moisture (g/Nm^3)	33.3	33.8	34.3
Flame temperature ($^{\circ}$C)	2303	2294	2296
HMT ($^{\circ}$C)	1489	1491	1492
Si (%)	0.40	0.38	0.38
S (%)	0.020	0.019	0.018
MgO (%)	7.49	7.17	7.29
CaO/SiO$_2$ (-)	1.23	1.26	1.27

at finding the operating parameters that give optimum results for a particular furnace.

Chapter 7

CONCLUSIONS

Mathematical modelling of the blast furnace has been carried out in stages in the present work. The raceway region has been modelled to predict the adiabatic flame temperature for given blast parameters. Another model is developed to determine the required blast humidity to maintain certain adiabatic flame temperature. Presence of ash in coal and coke and gasification of silica in the raceway have been incorporated into the model. Important findings of the study are as follows:

1. Flame temperature increases by 0.7 per unit increase in blast temperature.

2. Flame temperature decreases by 5.5 °C per g/Nm^3 of moisture in the blast.

3. Flame temperature increases by around 43^OC per unit % increase in oxygen enrichment of the blast.

4. Flame temperature decreases by about 1.9 °C per 1 g/Nm^3 injection of coal.

5. The flame temperature decreases by 1.8 to 11 °C for increase of 1 % ash in coke depending upon whether silica is gasified or not.

6. Injection of lime of $1g/Nm^3$ decreases the flame temperature by 1.1 to 1.5 depending upon presence of undecomposed carbonates up to 10 %.

Heat balance in the lower zone of furnace has been used to determine the fuel requirement of the furnace. Important parameters which affect the heat balance include the shaft efficiency, heat losses, gangue to iron weight ratio in the burden, blast parameters, coal injection and coke reactivity etc. The model may be used to evaluate the reported data of a plant and the scope for improvement. Analysis of the data from the literature for a number of modern and large blast furnaces shows that the shaft efficiency could be around 80 to 90 %. Study shows that efforts should be made to operate the blast furnace at as high flame temperature as possible without causing irregularities such as hearth breakout and tuyere burning. Oxygen enrichment of the blast should be practised when the maximum limit of increasing the blast temperature and decreasing the blast humidity have been reached.

Amount, composition and temperature of outgoing flue gases are determined in the third stage of modelling by making overall mass and heat balance of the process. Access to reliable plant data regarding top gas composition and temperature are required for the validity of the model.

The last stage of modelling has been aimed at finding the composition and amount of the intermediate slags formed in the upper and lower bosh parts of the furnace. The melting points of the slags are determined using ternary Al_2O_3-CaO-SiO_2 diagram. Melting point of the bosh slag decreases from 1690 to 1540°C, when lime is injected along with coal to have lime to coal weight ratio of 0.2 at coal injection rate of 2g/mole or 132 Kg/thm.

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APPENDIX

COMPUTER PROGRAMME
FOR SOLVING 4 STAGE MODEL EQUATIONS

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REAL Wck,Wl,Oe,O2,N2,Hdem(10)
REAL Acl,Ack,Aclsi,Aclfe,Aclal,Acksi,Ackfe,Ackai
REAL Ocl,Ncl,Ccl,Hcl,FCck,Lsi,Lca,Lmg,Lal,Lcaco3,f
REAL Mn2
REAL Hcrack
REAL Sh2,Sn2,Sco,Ssio
REAL Tf,Tc,Tbosh
REAL Wcl(10),Wlcac
REAL Tb,a(10,10),c(10),y(10)
REAL Mh2o(10),or(10),sr(10)
REAL cps,cpsio,cpco,cph2,cpco2,cpn2,cpo2tb,cpn2tb,cpc
REAL ac1,bc1,cc1,ac2,bc2,cc2,ac3,bc3,cc3,ac4,bc4,cc4
REAL ac5,bc5,cc5,ac6,bc6,cc6
REAL ac7,bc7,cc7,ac8,bc8,cc8,ac9,bc9,cc9
REAL Hffeo,Hfsi,Hfmn,Hfp,Hfh2o,Hfcac,Hslag,Hhm,cpfe
REAL fc,fsi,fmn,fp,Mbn2,Mbh2,Hfco,Hffo3,Hfsio
REAL K1,K2,Mfe2
REAL u(10,10),v(10,10),vr(10),ur(10),p(10),bs(10),s(10)
REAL ur1,ur2,d1,d2,H4
REAL CL,CK,BL,SL,LM,Mst,Tco,Tco2,Th2,Th2o,Tn2,FEcl,FEck,FEot
REAL FEin,CAlm,O2ty,N2ty,Hin,H1,H2,H3,Stpg,Hfco2
REAL C1,C12,C22,C2,C3,C4,C5,C6,C7,C8
REAL root,cf,ffes,Tg,Tgp,si,ca,mg,al,rmn,fs,ks
REAL Wcoal(10),Wcoke(10),Blast(10),Wfuel(10),Wslag(10)
REAL ph2o(10),Wlime(10),qa(10),qb(10),qc(10),qd(10),qe(10)
REAL Tgt(10),tt(10),t,rr(10),Hls,Loy,xms,msck,gr0
REAL por,h(10),FOin,FEOin,H5
REAL Wcs(10),Wbs(10),lmpt(10),eta,ffeos
REAL bca(10),bsi(10),bmg(10),bal(10)
REAL slca(10),slmg(10),slsi(10),slal(10),slmn(10)
REAL bs1(10),bs2(10),slfe(10),sls(10)
REAL coal(10),bs3(10),bs4(10),bs5(10),bs6(10)
REAL Wsit,Wslib(10),sit,cat,mgt,alt
REAL sib(10),cab(10),mgb(10),alb(10),sb(10),feb(10),mnb(10)
REAL nn2,nh2,ncao,nmgo,nAl2o3,siuib,mnuib
REAL rft(10),bt(10),oxy(10),Gtm(10),PGtm(10)
REAL Hloss(10),efcy(10),rzt(10),L,tl,L1,tpc,to,tl1

INTEGER j,zt,i3
character yy1*20,yy2*20,yz1*20,yz2*22,yz3*20,yz4*20,yz5*20
```

```
character yz6*20,yz7*20,yz8*20,yz9*20,yz10*20,yz11*20
character yz12*20,yz13*20,yz14*20,yz15*20,yz16*20,yz17*20
character yz18*20,yz19*20,yz20*20,yz21*20,yz22*20
character yz23*20,yz24*20,yz25*20,yz26*20,yz27*20
character yz28*20,yz29*23,yz30*24,yz31*24
character yz32*22,yz33*24,yz34*24,yz35*23,yz36*23,yz37*23
open(20,file='datatb.in')
open(21,file='result.out')
read(20,*)Acl,Aclfe,Aclal,Aclsi,Ocl,Ncl,Hcl,Ccl,Scl
read(20,*)Ack,Ackfe,Ackal,Acksi,FCck,xms
read(20,*)si,ca,mg,al,Loy,f
read(20,*)Ha,Hb,Hc,Hd,He,calv
read(20,*)ac1,bc1,cc1
read(20,*)ac2,bc2,cc2
read(20,*)ac3,bc3,cc3
read(20,*)ac4,bc4,cc4
read(20,*)ac5,bc5,cc5
read(20,*)ac6,bc6,cc6
read(20,*)ac7,bc7,cc7
read(20,*)ac8,bc8,cc8
read(20,*)ac9,bc9,cc9
read(20,*)Hfh2o,Hffe,Hfsi,Hfmn,Hfp,Hfcac
read(20,*)Hffeo,Hslag,Hhm,Hfco,Hfch2
read(20,*)Hffo3,Hfsio,Hfco2,Hvp
read(20,*)fcp,fsip,fmnp,fpp,fsp,rmnp,ks
read(20,*)Tb,Tf,Tbosh,Hls,jt,dwcl,zt
read(20,*)por,eta,Oe
read(20,*)or(1),or(2),or(3),or(4),or(5),or(6),or(7)
read(20,*)sr(1),sr(2),sr(3),sr(4),sr(5),sr(6)
read(20,*)lmpt(10),ffeos
write(21,*)Acl,Aclfe,Aclal,Aclsi,Ocl,Ncl,Hcl,Ccl,Scl
write(21,*)Ack,Ackfe,Ackal,Acksi,FCck,xms
write(21,*)si,ca,mg,al,Loy,f
write(21,*)Ha,Hb,Hc,Hd,He,calv
write(21,*)ac1,bc1,cc1
write(21,*)ac2,bc2,cc2
write(21,*)ac3,bc3,cc3
write(21,*)ac4,bc4,cc4
write(21,*)ac5,bc5,cc5
write(21,*)ac6,bc6,cc6
write(21,*)ac7,bc7,cc7
write(21,*)ac8,bc8,cc8
write(21,*)ac9,bc9,cc9
write(21,*)Hfh2o,Hffe,Hfsi,Hfmn,Hfp,Hfcac
write(21,*)Hffeo,Hslag,Hhm,Hfco,Hfch2
```

```
write(21,*)Hffo3,Hfsio,Hfco2,Hvp
write(21,*)fcp,fsip,fmnp,fpp,fsp,rmnp,ks
write(21,*)Tf,Tbosh,Hls,jt,dwcl,zt
write(21,*)por,eta,Oe
write(21,*)or(1),or(2),or(3),or(4),or(5),or(6),or(7)
write(21,*)sr(1),sr(2),sr(3),sr(4),sr(5),sr(6)
write(21,*)lmpt(10),ffeos
 yy1  ' Blast Moist g/Nm3   '
 yy2=' Blast Temp    C = '
 yz1=' Coke Rate  Kg/thm = '
 yz2='Coal Rate  Kg/thm  = '
 yz3=' Fuel Rate  Kg/thm = '
 yz4=' Cast Slag  Kg/thm = '
 yz5=' Blast Rate Nm3/thm= '
 yz6=' Lime Rate  Kg/thm = '
 yz7=' CO (%)        = '
 yz8=' CO2(%)        = '
 yz9=' H2 (%)        = '
 yz10=' N2(%)        = '
 yz11=' Top Gas Temp (C) = '
 yz12=' Top Gas   Nm3/thm = '
 yz13=' Replacement Ratio = '
 yz14=' Eta-CO (%)       = '
 yz15=' New Gangue Ratio  = '
 yz16=' SiO2 (%)       = '
 yz17=' CaO  (%)       = '
 yz18=' MgO  (%)       = '
 yz19=' Al2O3(%)       = '
 yz20=' FeO  (%)       = '
 yz21=' MnO  (%)       = '
 yz22=' CaO/SiO2       = '
 yz23=' (CaO+MgO)/SiO2   = '
 yz24=' S   (%)       = '
 yz25=' Stack Slag Kg/thm = '
 yz27=' Bosh Slag  Kg/thm = '
 yz28=' LoI in Lime (%)    '
 yz29='Heat Losses(cal/mole)= '
 yz30='Shaft Efficiency(%) = '
 yz31='   RAFT (K)     = '
 yz32='Heat Demand(Mcal/thm)'
   yz33='Blast Temperature(C)= '
   yz34='Oxygen enrichment(%)= '
   yz35='Reserve Zone Temp.(K)= '
 yz36='Heat Losses(Gcal/thm)= '
 yz37='Heat Losses(Pct )  = '
```

```
c--------------------------------------------------------------------
c      gr0    gangue to iron ratio in burden
c      snfo   % of fe2o3 in sinter
c      rmnp . % recovery of manganese
c      fcp  : % of carbon in hotmetal
c      fsip · % of silicon in hotmetal
c      fmnp . % of manganese in hotmetal
c      fsp  · % of sulphur in hotmetal
c      fpp  ·% of phosphorus in hotmetal
c      Hrhm : heat of dissociation of silica,mno and p2o5
c--------------------------------------------------------------------
       gor=por*(or(1)+or(2)+or(3)+or(4))
       gsr=(100 0-por)*(sr(1)+sr(2)+sr(3)+sr(4))
       gr0=(gor+gsr)/(por*or(7)+(100 0-por)*sr(5))
       srfo=(sr(5)-sr(6)*0 78)*1 43
       rmn=rmnp/100.0
       fc =fcp/100 0
       fsi=fsip/100 0
       fmn=fmnp/100 0
       fs =fsp/100.0
       fp =fpp/100.0
       ffe=1-fc-fsi-fmn-fp-fs
       Wcl(1)=0.0
       Wcl(2)=2 0
       Wcl(3) -2.0
       Wcl(4)=2.0
       Wcl(5)=2.0
c      Wcl(1)=1.0
c      Wcl(2)=1.25
c      Wcl(3)=1.5
c      Wcl(4)=1.75
c      Wcl(5)=2.0
       rft(1)  =2073.0
       rft(2)  =2073.0
       rft(3)  -2073.0
       rft(4)  =2073.0
       rft(5)  =2073.0
         bt(1)  =900 0
       bt(2)  =900 0
       bt(3)  =900 0
       bt(4)  =900 0
       bt(5)  -900.0
         oxy(1)  =2.0
         oxy(2)  -2 0
         oxy(3)  =2.0
```

```
      oxy(4)  =2.0
      oxy(5)  =2.0
   Hloss(1) =Hls
   Hloss(2)=Hls
   Hloss(3) =Hls
   Hloss(4) =Hls
   Hloss(5)=Hls
   efcy(1) =0.65
   efcy(2) =0 65
   efcy(3) =0 65
   efcy(4) =0 65
   efcy(5) =0.65
      rzt(1)  =1123 0
      rzt(2)  =1123.0
      rzt(3)  =1123 0
      rzt(4)  =1123 0
      rzt(5)  =1123.0
      Mh2o(1) =0.005
      Mh2o(2)  =0.005
      Mh2o(3)  =0.01
      Mh2o(4)  =0 015
      Mh2o(5) =0 02
      Impt(1) =0 0
      Impt(2) =0 0
      Impt(3)  =10.0
      Impt(4) =15.0
      Impt(5) =20.0
      i3=0
      f=0.5
c     ack=0.01
c     acl=0 01
      Loy =20.0

      do 70 j =1,5
      Impt(j)=0.00
      Mh2o(j)=0.01
      Wl   =Impt(j)*Wcl(j)/100.0
      Hls  =Hloss(j)
      eta  =efcy(j)
      Tbosh  =rzt(j)
        tb =bt(j)+273.0
         tc=1773.0
       Tbosha =Tbosh-298.0
       Tbsd   =Tbosh-50.0
       Tbsda  =Tbosha-50.0
```

```
          Lcaco3=(Loy/44 0)
          Lca=(ca*(1-Loy/100))
          Lsi=(si*(1-Loy/100))
          Lmg=(mg*(1-Loy/100))
          Lal=(al*(1-Loy/100))
          o2cl  Acl*Aclfe*1 5/1.6e6 + ocl/3.2e3
          Wlcac=Lcaco3*1 0e-2
          Wlsl=1.0-Lcaco3*0 44
          Wclsl=Acl*(1 0-Aclfe*0 01)*0.01
          Wcksl  Ack*(1 0-Ackfe*0 01)*0.01
          Hrhm=fsi*HfSi/28 0+fmn*Hfmn/55 0+fp*Hfp/62.0
          Hrwl  Hfcac*Wlcac
          Hrwcl=Hffo3*Acl*Aclfe/1 6e6 +Hcrack(Ccl,Hcl,Scl,Ocl)
  c       VARIABLES
          Wslcl=0 01*Acl*(1.0-Aclfe*0 01)
          Wslck=0.01*Ack*(1 0-Ackfe*0 01)
          Wslli=1 0-Lcaco3*0 44
          oca=Oxy(j)*0 01
          O2 =0.21+oca
          N2 =1.0-O2
  c       *****************
          if (i3.ne.1) go to 777
  779     continue
          Rcg= 0 00112
  c       variables 1  CO 2 SIO 3 SIO2 4 Fe 5 COKE
  c       CARBON BALANCE
          v(1,1)=12.0
          v(1,2)=0.0
          v(1,3)=0 0
          v(1,4)=0.0
          v(1,5)= - (0.01*Fcck)
          vr(1)=0.01*Wcl(j)*Ccl+Wl*Lcaco3*0.12
  c       SILICON BALANCE
          v(2,1)=0.0
          v(2,2)= 1.0
          v(2,3)= 1.0
          v(2,4) = 0.0
          v(2,5)= - (Ack*Acksi/6 0E5)
          vr(2)=(Wcl(j)*Acl*Aclsi/6.0E5)+Lsi*Wl/60 0
  c       SiO BALANCE
          v(3,1)= 0.0
          v(3,2)= 1.0
          v(3,3)= 0 0
          v(3,4)= 0.0
          v(3,5)= -(f*Ack*Acksi)/6 0E5
```

```
        vr(3)  (1*Wcl(j)*Acl*Aclsi)/6 0E5
c    IRON BALANCE
        v(4,1)  0 0
        v(4,2)  0 0
        v(4,3)  0 0
        v(4,4)  1 0
        v(4,5)  -(2*Ack*Ackfe)/1 6E6
        vr(4)-(2*Wcl(j)*Acl*Aclfe)/1.6E6
c    OXYGEN BALANCE
        v(5,1) - 1 0
        v(5,2)- -1 0
        v(5,3)  0 0
        v(5,4)= 0 0
        v(5,5)= -(3*Ack*Ackfe)/1 6E6
        vr(5)- 2*O2+(Wcl(j)*Ocl)/1.6E3+0.02*Wl*Lcaco3+
     *  (3*Wcl(j)*Acl*Aclfe)/1.6E6+mh2o(j)
        Call SOLN(5,v,vr,s)
c    HYDROGEN BALANCE
        nh2=mh2o(j)+(Wcl(j)*Hcl)/2.0E2
c    NITROGEN BALNCE
        nn2=N2+(Wcl(j)+Wl)*Rcg+(Ncl*Wcl(j))/2.8E3
c    CaO BALANCE
        ncao=(Wl*Lca)/56.0
c    MgO BALANCE
        nmgo-(Wl*Lmg)/40.0
c    Al2O3 BALANCE
        nAl2o3=(Wcl(j)*Acl*Aclal)/1.02E6+(s(5)*Ack*Ackal)/1.02E6+
     *  (Wl*Lal)/1 02E2
c    INPUT SENSIBLE HEATS
c    HEAT OF FORMATION OF CO GAS
        Sreac1=s(1)*Hfco
c    HEAT OF FORMATION OF SIO GAS
        Sreac2=-s(2)*(Hfsio)
c    SENSIBLE HEAT OF OXYGEN
        So2-O2*cps(ac8,bc8,cc8,tb)
c    SENSIBLE HEAT OF NITROGEN
        Sn2=N2*cps(ac6,bc6,cc6,tb)
c    SENSIBLE HEAT OF WATER
        Sh2o=mh2o(j)*cps(ac9,bc9,cc9,tb)
c    SENSIBLE HEAT OF COKE
        Washck 0.01*(S(5)*Ack)
        Scoke Washck*0.25*(tc-298)+((S(5)*Fcck)/1.2E3)*cps(ac1,bc1,cc1,tc)
c    OUTPUT SENSIBLE HEATS
c    HEAT OF FORMATION OF H2O
        Sreac3-mh2o(j)*Hfh2o
```

```
c       SENSIBLE HEAT OF IRON
        Sfe=s(4)*(10 6*(tf-1873)+280 0*56 0)
c       SENSIBLE HEAT OF (Sio2+Al2o3+Cao+Mgo)
        Sslag1=(60 0*S(3)+102 0*nAl2o3+56.0*ncao+40 0*nmgo)
c       Sslag=Sslag1*(0 25*(tf-1873)+480)
c       HEAT OF DISSOCIATION OF Fe2o3
        SFe2o3=(S(4)/2.0)*Hffo3
c       HEAT OF CRACKING
          Scrack=Hcrack(Ccl,Hcl,Scl,Ocl)*Wcl(j)+Wl*Hrwl
        SLH=Sreac1+Sreac2+So2+Sn2+Sh2o+Scoke-Sreac3+
     *  S(4)*(10 6*1575 0-280 0*56)- Sslag1*(Hslag-0.25*1575)-
     *  SFe2o3-Scrack
          tfa=2000
 999      continue
          tf=tfa
          Sh21=nh2*cpa(ac4,bc4,cc4,tf)
          Sco1=s(1)*cpa(ac3,bc3,cc3,tf)
          Sn211=nn2*cpa(ac6,bc6,cc6,tf)
          Ssio1=s(2)*cpa(ac2,bc2,cc2,tf)
          SRH=Sh21+Sco1+Sn211+Ssio1+Sslag1*0 25+S(4)*10.6
          tfa=(SLH/SRH)+298
          if (abs(tfa-tf) gt 1 0) go to 999
          write(6,*) tfa
        rft(j)=tfa
          p(2) s(5)
        goto 778
 777    continue
          tf=rft(j)
c       raceway variables 1=CO  2= coke  3= H2O  4= Fe  5= slag 6= SiO
c       CARBON BALANCE
        u(1,1)=12.0
        u(1,2)=-(0.01*FCck)
        u(1,3)=0.0
        u(1,4)=0.0
        u(1,5) 0.0
        u(1,6) 0.0
        ur(1) =0.01*Wcl(j)*Ccl+12.0*Wl*Wlcac
c       OXYGEN BALANCE
        u(2,1)=1.0
        u(2,2)=-(Ack*Ackfe*3.0/(1.6E6))
        u(2,3) -1.0
        u(2,4) 0.0
        u(2,5)=0.0
        u(2,6)=-1.0
        d1   =Wcl(j)*0.01*(Ocl/16+(Acl*Aclfe*3.0/1.6E4))
```

```
         d2    (Wlcac*Wl+O2)*2 0
         ur(2) =d1 +d2
c     SILICON BALANCE
         u(3,1)=0.0
         u(3,2)=-(Ack*Acksi*f/6.0E5)
         u(3,3)=0.0
         u(3,4)=0.0
         u(3,5)=0 0
         u(3,6)=1 0
         ur(3) =(Wcl(j)*Acl*Aclsi*f/6 0E5)
c     IRON BALANCE
         u(4,1)=0 0
         u(4,2)=-(Ack*Ackfe*112 0/1.6E6)
         u(4,3)=0 0
         u(4,4)=1.0
         u(4,5)=0.0
         u(4,6)=0 0
         ur(4) =(Wcl(j)*Acl*Aclfe*1.12/1 6E4)
c     SLAG BALANCE
         u(5,1)=0.0
         u(5,2)=-Wcksl
         u(5,3)=0.0
         u(5,4)=0.0
         u(5,5)=1 0
         u(5,6)=60.0
         ur(5) =Wcl(j)*Wclsl+Wl*Wlsl
c     HEAT BALANCE
         cpc  =cps(ac1,bc1,cc1,Tc)
         cpsio=cps(ac2,bc2,cc2,Tf)
         cpco =cps(ac3,bc3,cc3,Tf)
         cph2=cps(ac4,bc4,cc4,Tf)
         cpco2=cps(ac5,bc5,cc5,Tf)
         cpn2=cps(ac6,bc6,cc6,Tf)
         cpo2tb=cps(ac8,bc8,cc8,Tb)
         cpn2tb=cps(ac6,bc6,cc6,Tb)
         cph2o =cps(ac9,bc9,cc9,Tb)
         cpfe =0.2E-3*(Tf**2)+(Tf*9.77)-4636 79
         u(6,1)=-Hfco +cpco
         ur4  =Ack*2.5e-3*(Tc-298.0)
         u(6,2)=-(ur4+(FCck*cpc/1.2E3))
         u(6,3)=Hfh2o+cph2-cph2o
         u(6,4)=(Hffo3*0 5)/56.0+280.0+((10 56*(Tf-1873))/56.0)
         u(6,5) =Hslag+(Tf-1873 0)/4.0
         u(6,6)  Hfsio+cpsio
         ur1   =-(Wcl(j)*Hcrack(Ccl,Hcl,Scl,Ocl)+Wl*Hrwl)
```

```
      ur2   =O2*cpo2tb+N2*cpn2tb-Wcl(j)*Hcl*cph2/200 0
      Mn2   =N2+(Wcl(j)*Ncl/2800 0)+((Wcl(j)+Wl)*1.12E-3)
      ur(6) =ur1+ur2-Mn2*cpn2
      call SOLN(6,u,ur,p)
      if (p(3) .lt 0 0) then
         Mh2o(j)- 0 0
      go to 779
      else
         Mh2o(j)=p(3)
      endif
 778  continue
c     SECOND STAGE MODELLING
c---------------------------------------------------------------
c     Mbh2    · moles of hydrogen
c     Mbn2      moles of nitrogen
c     cpo2tb  · specific heat of oxygen at Tb temperature
c     cpn2tb    specific heat of nitrogen at Tb temperature
c     Wsit    : weight of silica at tuyere/ton of hotmetal
c     p2      . weight of coke
c     y(5)    : weight of hotmetal
c     cat     : weight of calcium at tuyere
c     alt     : weight of alumina at tuyere
c     FOin    . moles of iron as fe2o3
c     FEOin   . moles of iron as feo
c     Wbd     : weight of burden /ton of hotmetal
c     Wor       weight of ore /ton of hotmetal
c     Wsn     · weight of sinter /ton of hotmetal
c     Wcoke   . weight of coke /ton of hotmetal
c     Wcoal   · weight of coal /ton of hotmetal
c     Wfuel   · weight of total fuel
c     Wslib   . weight of slag /ton of hotmetal
c     BSsi      weight of silica in bosh
c     BSca    · weight of calcium in bosh slag
c     BSmg    . weight of magnesium in bosh slag
c     BSal    : weight of al2o3 in bosh slag
c     Wbs     . weight of bosh slag
c     bs3     : basicity of slag in stack
c     bs4     : basicity of slag in stack
c     cka     : weight of ash in coke
c     cla     . weight of ash in coal
c     CSsi    . weight of silica in cast slag
c     CSca      weight of calcium in cast slag
c     CSmg    · weight of magnesium in cast slag
c     CSal    . weight of alumina in cast slag
c     CSmn      weight of manganese in cast slag
```

```
c    sib    % of silica in bosh slag
c    cab    % of calcium in cast slag
c    mgb    % of magnesium in cast slag
c    bs5    basicity in bosh slag
c    bs6    basicity in bosh slag
c    slsi   % silica in cast slag
c    slca   : % calcium in cast slag
c    slmg   % magnesium in cast slag
c    slal   % aluminium in cast slag
c    sls    % sulphur in cast slag
c    slmn   % manganese in cast slag
c    slfe   % feo in cast slag
c    bs1    basicity in cast slag
c    bs2    · basicity in cast slag
c-------------------------------------------------------------------
c    variable  1=Coke  2 = FeO  3= Fe  4= CO  5= hot metal 6= slag
c    Oxygen balance in lower zone of BF
     a(1,1)=-(1 5*Ack*Ackfe)/1 6E6
     a(1,2)=-0 5
     a(1,3)=0 0
     a(1,4)=0 5
     a(1,5)=-(fsi/28 +fmn/110.+fp*2.5/62 )
     a(1,6)=ffeos*0 01/144.
c    Iron Balance in lower zone of BF
     a(2,1)=-Ack*Ackfe*0 7E-4
     a(2,2)=-56 0*0 95
     a(2,3)=-56.0
     a(2,4)=0 0
     a(2,5)=ffe
     a(2,6)=0 95*0.56*ffeos/72 0
c    Carbon balance in the lower part of BF
     a(3,1)=-FCck/100
     a(3,2)=0.0
     a(3,3)=0.0
     a(3,4)=12.
     a(3,5)=fc
     a(3,6)=0 0
c    Slag Balance
     a(4,1)=-Wcksl
     a(4,2)=-gr0*56.0*0.95
     a(4,3)=-gr0*56.0
     a(4,4)=0 0
     a(4,5)=(2 14*fsi-(1-rmn)*1 29*fmn/rmn)
     a(4,6)=1 0-ffeos*0.01-fs*ks
c    Shaft Equilibrium  FeO + CO = Fe + CO2
```

```
        a(5,1)=0 0
        a(5,2)=0 0
        a(5,3)= 1/0.95
        K2=10**(-(4350 0/(4 606*Tbsd))+0 51)
        K1=10**((4300.0/(4.606*Tbsd))-1 14)
        a(5,4)=-eta*K1/(1+K1)
        a(5,5)-0.0
        a(5,6)=0 0
c       Heat balance in the Lower Zone of BF
        a(6,1)=-(cps(ac1,bc1,cc1,Tbsd)*FCck/12.0+Ack*0 25*Tbsda)*0 01
     1  +Ack*Ackfe*hffe/1 6e6
        a(6,2)--cps(ac7,bc7,cc7,Tbsd) HIffeo-0 25*Tbsda*gr0*56.0*0 95
        a(6,3)=-ac9*Tbsda-0 25*Tbsda*56 0*gr0
        a(6,4)=cps(ac3,bc3,cc3,Tbosh)-Hfco
        a(6,5)=Hhm+Hrhm-0 25*(142*fp/62+(1.-rmn)*1 29*fmn/rmn+fs)*Tbsda
        a(6,6)=Hslag-ffeos*Hffeo/7200 0-0 25*Tbsda*fs*ks
        SHh2=cps(ac4,bc4,cc4,Tbosh)
        SHn2=cps(ac6,bc6,cc6,Tbosh)

        cpc  =cps(ac1,bc1,cc1,Tc)
        cpsio=cps(ac2,bc2,cc2,Tf)
        cpco =cps(ac3,bc3,cc3,Tf)
        cph2=cps(ac4,bc4,cc4,Tf)
        cpco2=cps(ac5,bc5,cc5,Tf)
        cpn2=cps(ac6,bc6,cc6,Tf)
        cpo2tb=cps(ac8,bc8,cc8,Tb)
        cpn2tb=cps(ac6,bc6,cc6,Tb)
        cph2o =cps(ac9,bc9,cc9,Tb)
        cpfe =0 2E-3*(Tf**2)+(Tf*9.77)-4636.79
        Mn2  =N2+(Wcl(j)*Ncl/2800.0)+((Wcl(j)+Wl)*1 12E-3)
        Mbh2=(Wcl(j)*Hcl)/200 0+Mh2o(j)
        Mbn2=((Wcl(j)+Wl)*1.12E-3)+(Wcl(j)*Ncl/2800 0)+0.79-Oea
c       THE COEFFICIENTS OF THE MATRIX
        c(1)=Wl*Wlcac+Wcl(j)*o2cl+O2+mh2o(j)/2.0
        c(3)=Wcl(j)*Ccl*0 01+Wl*Wlcac*12
        c(2)-Wcl(j)*Acl*Aclfe*0 7e-4
        c(4)=Wcl(j)*Wclsl
        c(5)=Mbh2*eta*K2/(1 0+K2)
        c6a=O2*cpo2tb
        c6b=N2*cpn2tb
        c6c=Mh2o(j)*(cph2o-Hfh2o)
        c6d=Mbh2*SHh2+Mbn2*SHn2+Hls*0 8+Wlsl*Wl*0.25*Tbsda
        c(6)=c6a+c6b+c6c-Wcl(j)*Hrwcl-Wl*Hrwl-c6d
        call SOLN(6,a,c,y)
        call bdn(por,or(7),y(2),y(3),sr(5),srfo,sr(6),h)
```

```fortran
c     SLAG FORMED IN THE TUYERE
      Wsit=(p(2)*Wcksl+Wcl(j)*Wclsl+Wl*Wlsl)*1000 0/y(5)
      sit =(p(2)*Ack*Acksi+Wcl(j)*Acl*Aclsi+Wl*Lsi*10000 0)*0 1/y(5)
      cat =Wl*Lca*1000 0/y(5)
      mgt =Wl*Lmg*1000 0/y(5)
      alt =((p(2)*Ack*Ackal+Wcl(j)*Acl*Aclal+Wl*Lal*10000 0)*0 1)/y(5)
      write(6,*)alt
      FOin=h(4)*1000.0/y(5)
      FEOin=h(5)*1000 0/y(5)
      Wbd =h(1)*1000 0/y(5)
      Wor =h(6)*1000 0/y(5)
      Wsr =h(7)*1000.0/y(5)
      Wcoke(j)=y(1)*1000 0/y(5)
      Wcoal(j)=Wcl(j)*1000 0/y(5)
      Wfuel(j)=Wcoke(j)+Wcoal(j)
      Wlime(j)=Wl*1000 0/y(5)
      Wslag(j)=1000 0*y(6)/y(5)
      Wslib(j)=Wslag(j)-Wsit
      siuib=60000*fsi/28.0
      mnuib=71000*fmn/55 0
      Blast(j)=22400.0*(1 0+Mh2o(j))/y(5)
c     SLAG COMING TO THE BOSH FROM THE STACK
      BSsi=(Wor*or(1)+Wsr*sr(1))*0 01-Wlime(j)*Lsi
      BSca=(Wor*or(2)+Wsr*sr(2))*0.01-Wlime(j)*Lca
      BSmg=(Wor*or(3)+Wsr*sr(3))*0.01-Wlime(j)*Lmg
      BSal=(Wor*or(4)+Wsr*sr(4))*0 01-Wlime(j)*Lal
      Wbs(j)=BSsi+BSca+BSmg+BSal
      bsi(j)=BSsi*100.0/Wbs(j)
      bca(j)=BSca*100.0/Wbs(j)
      bmg(j)=BSmg*100.0/Wbs(j)
      bal(j)=BSal*100.0/Wbs(j)
      bs3(j)=BSca/BSsi
      bs4(j)=(BSca+BSmg)/BSsi
      cka =Wcoke(j)*Ack*0.01
      cla =Wcoal(j)*Acl*0.01
      CSsi=(Wor*or(1)+Wsr*sr(1)+cka*Acksi+cla*Aclsi)*0.01-fsi*2.1E3
      CSca=(Wor*or(2)+Wsr*sr(2))*0.01
      CSmg=(Wor*or(3)+Wsr*sr(3))*0.01
      CSal=(Wor*or(4)+Wsr*sr(4)+cka*Ackal+cla*Aclal)*0.01
      CSmn=(1.0-rmn)*fmn*1290.0/rmn
      Wcs(j)=(CSsi+CSca+CSmg+CSal+CSmn)/(1 0-ffeos*0.01-fs*ks)
c     SLAG FORMING AT THE BOSH
      sib(j) =(CSsi-sit+siuib)*100.0/Wslib(j)
      cab(j) =(CSca-cat)*100.0/Wslib(j)
      mgb(j) =(CSmg-mgt)*100.0/Wslib(j)
```

```
        alb(j) =(CSal-alt)*100 0/Wslib(j)
          write(6,*)alb
        feb(j) =ffeos*Wslag(j)/Wslib(j)
        sb (j) =ks*fsp*Wslag(j)/Wslib(j)
        mnb(j) =(CSmn+mnuib)*100 0/Wslib(j)
        bs5(j) =cab(j)/sib(j)
        bs6(j) =(cab(j)+mgb(j))/sib(j)
c       **************
        slsi(j)=CSsi*100.0/Wcs(j)
        slca(j)=CSca*100 0/Wcs(j)
        slmg(j)=CSmg*100 0/Wcs(j)
        slal(j)=CSal*100 0/Wcs(j)
        sls(j) =ks*fsp
        slmn(j)=CSmn*100.0/Wcs(j)
        slfe(j)=ffeos
        bs1(j) =slca(j)/slsi(j)
        bs2(j) =(slca(j)+slmg(j))/slsi(j)
        ph2o(j)=Mh2o(j)*1.8E4/22 4
c       ph2o(j)=Mh2o(j)*1.8E4/((1.0+Mh2o(j))*22.4)
c       THIRD STAGE MODELLING
c--------------------------------------------------------
c    CL    · weight of coal /ton of hotmetal
c    CK    : weight of coke /ton of hotmetal
c    LM    : weight of lime /ton of hotmetal
c    SL    : weight of slag /ton of hotmetal
c    xms   : % moisture in coke on dry basis
c    msck  : moisture in coke in moles
c    O2ty  : moles of oxygen /ton of hotmetal
c    N2ty  : moles of nitrogen /ton of hotmetal
c    ffes  : % of iron in slag
c    Mst   · moles of H2o /ton of hotmetal
c    fecl  : moles of iron in coal
c    feck  : moles of iron in coke
c    FEot  : moles of iron out
c    FEin  : mloes of iron in
c    CALm  :moles of cacao3
c    Tco2  : moles of co2
c    Tco   : moles of co
c    Th2o  : moles of water
c    Th2   : moles of hydrogen
c    t     : total moles of gases
c--------------------------------------------------------
        CL=Wcoal(j)
        CK=Wcoke(j)
        LM=Wlime(j)
```

```
      SL=Wslag(j)
      BL=1000 0/y(5)
      msck=0 01*xms*CK/(18 0*(1 0-0 01*xms))
      O2ty=BL*O2
      N2ty=BL*N2
      ffes=0 56*ffeos/72 0
      Mst=BL*Mh2o(j)
      Tn2=Mn2*BL
      FEcl=CL*Acl*Aclfe/0.8E6
      FEck=CK*Ack*Ackfe/0.8E6
      FEot=(ffe*1000.0+ffes*SL)/56 0
      FEin=FEot-FEcl-FEck
      CAlm=LM*Lcaco3*1.0E-4
      C1=((CL*Ccl+CK*FCck)*0 01+12.0*CAlm-fc*1000 0)/12 0
      C12=(CL*Ocl/1 6E3)+2 0*BL*O2+Mst+2.0*CAlm+(FEcl+FEck)*1.5
      C22=h(3)*FEin+(fsi/14 0+fmn/55 0+fp/12.4)*1000 0
      C2=C12+C22
      C3=Mst+(CL*Hcl/200.0)
      C4=EXP((8650 0/773.0-7.59)/1.9)
      C5=C4-1.0
      C6=C2-C4*C2-C1-C3
      C7=C4*C1*(C2-C1)
      Tco2=root(C5,C6,C7,C1)
      Tco =C1-Tco2
      Th2o=C2-C1-Tco2
      Th2 =C1+C3+Tco2-C2
      t=Tco+Tco2+Th2+Tn2+Th2o
      C8  =(t-Th2o)*0 01
      tt(j)=t*22.4
      qa(j)=Tco/C8
      qb(j)=Tco2/C8
      qc(j)=Th2/C8
      qd(j)=(Tco2*100.0)/(Tco+Tco2)
      qe(j)=Tn2/C8
      Hin =Hfco*Tco+Hfco2*Tco2+O2ty*cpo2tb+N2ty*cpn2tb+Mst*cph2o
      H1  =Hfh2o*(Mst-Th2o)+Hfcac*CAlm+SL*Hslag+1000.0*Hhm
      H2  =(Hfsi*fsi/28.0+Hfmn*fmn/55 0+Hfp*fp/62.0)*1000.0
      H5  =(FOin+0.5*(FEcl+FEck))*Hffo3+FEOin*Hffeo
      H3  =H5-(ffes*SL*Hffeo/56.0)
      H4  =Hcrack(Ccl,Hcl,Scl,Ocl)*CL+Hls*BL+msck*(Hvp+cph2o)
      Stpg=Hin-H1-H2-H3-H4
      Tg=0.0
      Tgp=700.0
      itg=1
100   IF(abs(Tg-Tgp).le.3.0) GO TO 101
```

```
        if(itg ge 20)go to 101
        itg=itg+1
        Tg=Tgp
        cco =Tco*cf(ac3,bc3,cc3,Tg)
        cco2=Tco2*cf(ac5,bc5,cc5,Tg)
        ch2 =Th2*cf(ac4,bc4,cc4,Tg)
        ch2o=Th2o*cf(ac9,bc9,cc9,Tg)
        cn2 =Tn2*cf(ac6,bc6,cc6,Tg)
        Tgp =Stpg/(cco+cco2+ch2+ch2o+cn2)+298 0  `
        GO TO 100
101     Tgt(j)=Tg-273.0
        Hd1 =Tco*cps(ac3,bc3,cc3,Tg)+Tco2*cps(ac5,bc5,cc5,Tg)
        Hd2 =Th2*cps(ac4,bc4,cc4,Tg)+Th2o*cps(ac9,bc9,cc9,Tg)
        Hd3 =Tn2*cps(ac6,bc6,cc6,Tg)
        Hdem(j)=1.0E-3*(H1+H2+H3+H4+Hd1+Hd2+Hd3)
        tl=mh2o(j)
        tk=tb-273
        call RAF(tk,O2,tl,L)
           write(6,*) L
           tll=ph2o(j)
        to=60.0*(0.01*oxy(j)/(0.79-0.01*oxy(j)))
           tpc=((Wcl(j)*60 0)/(22 4*1.0E3))
           call RAFT(tk,tll,to,tpc,L1)
           write(6,*) L1
        Gtm(j)=(Hls*Blast(j)*1.0E-6)/22.4
           PGtm(j)=((Hls*Blast(j))/(Hdem(j)*224 0))
70      CONTINUE
        rr(1)=0.0
        do 71 j=2,jt
           rr(j)=(Wcoke(1)-Wcoke(j))/Wcoal(j)
71      continue
        write(21,80)
80      format(20x,'COMPUTED OPERATING VARIABLES')
        write(21,81)
81      format(19x,'----------------------------'//)
        write(21,39)
39      format(1x,80(1h_)//)
c       write(21,98)yz28
98      format(45x,a20)
c       write(21,83)(Loi(j),j=1,jt)
        write(21,84)yz31,(rft(j),j=1,jt)
c       write(21,201)yz31
c       write(21,83)(rft(j),j=1,jt)
        write(21,84)yz33,(bt(j),j=1,jt)
c       write(21,201)yz33
```

```
c       write(21,83)(bt(j),j=1,jt)
        write(21,84)yz34,(oxy(j),j=1,jt)
c       write(21,201)yz34
c       write(21,208)(oxy(j),j=1,jt)
        write(21,84)yz35,(rzt(j),j=1,jt)
c       write(21,201)yz35
c       write(21,83)(rzt(j),j=1,jt)
 208    format(/30x,5(f7.2,3x)/)
        write(21,84)yz29,(Hloss(j),j=1,jt)
c       write(21,201)yz29
 201    format(45x,a22)
c       write(21,83)(Hloss(j),j=1,jt)
        write(21,84)yz30,(efcy(j)*100,j=1,jt)
c       write(21,201)yz30
c       write(21,83)(efcy(j)*100,j=1,jt)
        write(21,84)yz2,(Wcoal(j),j=1,jt)
        write(21,39)
c       write(21,82)yz2
c82     format(45x,a20)
c       write(21,83)(Wcoal(j),j=1,jt)
c83     format(/30x,5(f7.1,3x)/)
        write(21,84)yy1,(ph2o(j),j=1,jt)
 84     format(/5x,a23,5x,5(f7.2,3x))
        write(21,84)yz1,(Wcoke(j),j=1,jt)
        write(21,85)yz13,(rr(j),j=1,jt)
        write(21,84)yz6,(Wlime(j),j=1,jt)
 85     format(/5x,a20,5x,5(f7 2,3x))
        write(21,84)yz3,(Wfuel(j),j=1,jt)
        write(21,84)yz4,(Wslag(j),j=1,jt)
        write(21,84)yz25,(Wbs(j),j=1,jt)
        write(21,84)yz27,(Wslib(j),j=1,jt)
        write(21,84)yz5,(Blast(j),j=1,jt)
        write(21,84)yz36,(Gtm(j),j=1,jt)
        write(21,84)yz37,(PGtm(j),j=1,jt)
        write(21,84)yz12,(tt(j),j=1,jt)
        write(21,84)yz11,(Tgt(j),j=1,jt)
        write(21,86)yz32,(Hdem(j),j=1,jt)
 86     format(/5x,a22,4x,5(f7.1,3x))
        write(21,91)
 91     format(/5x,'CAST SLAG COMPOSITION ')
        write(21,92)
 92     format(5x,'-------------------- ')
        write(21,85)yz16,(slsi(j),j=1,jt)
        write(21,85)yz17,(slca(j),j=1,jt)
        write(21,85)yz18,(slmg(j),j=1,jt)
```

```fortran
      write(21,85)yz19,(slal(j),j=1,jt)
      write(21,85)yz24,(sls(j),j=1,jt)
      write(21,85)yz20,(slfe(j),j=1,jt)
      write(21,85)yz21,(slmn(j),j=1,jt)
      write(21,85)yz22,(bs1(j),j=1,jt)
      write(21,85)yz23,(bs2(j),j=1,jt)
      write(21,13)
13    format(/5x,'STACK SLAG BASICITY ')
      write(21,14)
14    format(5x,'-------------------')
      write(21,85)yz16,(bsi(j),j=1,jt)
      write(21,85)yz17,(bca(j),j=1,jt)
      write(21,85)yz18,(bmg(j),j=1,jt)
      write(21,85)yz19,(bal(j),j=1,jt)
      write(21,85)yz22,(bs3(j),j=1,jt)
      write(21,85)yz23,(bs4(j),j=1,jt)
      write(21,15)
15    format(/5x,'BOSH SLAG BASICITY ')
      write(21,21)
21    format(5x,'----------------')
      write(21,85)yz16,(sib(j),j=1,jt)
      write(21,85)yz17,(cab(j),j=1,jt)
      write(21,85)yz18,(mgb(j),j=1,jt)
      write(21,85)yz19,(alb(j),j=1,jt)
      write(21,85)yz24,(sb(j),j=1,jt)
      write(21,85)yz20,(feb(j),j=1,jt)
      write(21,85)yz21,(mnb(j),j=1,jt)
      write(21,85)yz22,(bs5(j),j=1,jt)
      write(21,85)yz23,(bs6(j),j=1,jt)
      write(21,89)
89    format(/5x,'TOP GAS COMPOSITION(dry basis)')
      write(21,90)
90    format(5x,'-----------------------------')
      write(21,85)yz7,(qa(j),j=1,jt)
      write(21,85)yz8,(qb(j),j=1,jt)
      write(21,85)yz14,(qd(j),j=1,jt)
      write(21,85)yz9,(qc(j),j=1,jt)
      write(21,85)yz10,(qe(j),j=1,jt)
      write(21,72)
72    format(5x,40(1H*)//)
410   continue
      stop
      end
      SUBROUTINE  SOLN(me,u,c,y)
      dimension  u(10,10),c(10),y(10)
```

```
        mej=me+I
        do 100 im=I,me
100     u(im,mej)=c(im)
      do 115 i=I,me
        do 105 j=I,mej
          if(j EQ i) go to 105
          u(i,j)=u(i,j)/u(i,i)
105     continue
        u(i,i)=I
        do 115 ii=I,me
          if(i EQ ii) go to 115
          do 110 j=i+I,mej
110         u(ii,j)=u(ii,j)-u(i,j)*u(ii,i)
115   continue
        do 120 im=I,me
120       y(im)=u(im,mej)
      return
      end
      SUBROUTINE  bdn(a,n,b,c,d,e,f,x)
        real g,x12,x22,a,b,c,d,e,f,n,x(10),wo,ws
        g=(a*n+(100.0-a)*d)/1.0e4
        x(1)=56 0*(b+c)/g
        ws =x(1)*0.01*(100.0-a)
        wo =x(1)*0 01*a
        x12=e*3.0/160 0+f/72.0
        x22=e/80 0+f/72.0
        x(2)=x12/x22
        x(3)=(d*ws*x(2)+n*wo*1.5)/(d*ws+n*wo)
        x(4)=x(1)*((100.0-a)*e/160.0+a*n/112 0)*1 0e-4
        x(5)=x(1)*(100 0-a)*f/7.2e5
        x(6)=wo
        x(7)=ws
      return
      end


      SUBROUTINE RAF (a,b,c,G)
      real G,a,b,c
      G=((0.9341*a+8208.0*b-c*(2402-1.2177*a)+94 76)/(1 0+b+c))
      return
      end


      SUBROUTINE RAFT(a,b,c,d,G1)
      real G1,a,b,c,d
      G1=(1559.0+0 839*a-6 033*b+82.87*c-0 031*(16666*d)**2)
      return
```

```
        end

        REAL  FUNCTION   cps(a,b,c,t)
            real tI
             tI=298 0
             cps=(t-tI)*(a+b*(t+tI)*0 5-c/(t*tI))
             return
             end
        REAL  FUNCTION   cf(a,b,c,t)
            real tI
            tI=298 0
            cf=a+b*(t+tI)*0 5-c/(t*tI)
            return
            end


        REAL  FUNCTION   cpa(a,b,c,t)
            real t
            cpa=a+b*(t+298)*0 5-c/(t*298)
            return
            end


        REAL  FUNCTION   root(a,b,c,e)
            real d,x,y
            d=SQRT(b*b-4 0*a*c)
            x=(-b+d)/(2 0*a)
            y=(-b-d)/(2 0*a)
            if(x .LE  e) THEN
               root=x
            else
               root=y
            endif
            return
            end
         REAL  FUNCTION   Hcrack(a,b,c,d)
            real Hfco2,Hfh2o,hfso2
c           Hfco2  =94260 0
            Hfh2o  =58850.0
c           Hfso2  =218334.0
c           Hcrack =0.01*(a*Hfco2/12 0+b*Hfh2o/2.0+c*Hfso2/32.0)-d
c           Hcrack =0.01*a*5533 0/12 0
            Hcrack = 0.01*(d*Hfh2o/16 0+(b-d/8 0-c/16.0)*2766 5)
            return
            end
```

APPENDIX: DATA FILE

17 0 10 0 30 0 60 0 5 3 1 62 3 9 71 8 0 38

19 0 10 0 30 0 60 0 81 0 4 0

0 0236 0 9467 0 02476 0 00484 4 0 0 001

26420.0 32380 0 168980 0 117540 0 40250 0 7250 9

4 03 1.04E-3 2.04E5

7.7 0.74E-3 0 70E5

6 79 0 98E-3 0.11E5

6 52 0 78E-3 0.12E5

10 57 2.10E-3 2.06E5

6 83 0 90E-3 0.12E5

11 66 2.00E-3 0.67E5

7.16 1.00E-3 0.40E5

7 3 2.46E-3 0.0

57800.0 196800.0 217300 0 92050 0 367060 0 134510 0

63500 0 480 0 280 0 26420 0 5533 0

195450.0 193000.0 94260 0 30.0

4 19 0 95 0 1 0 217 0 061 70.0 20 19

1100 2273 0 1073 0 2000 0 5 2.2 1

33.3 0 65 3 75

1.7 0.2 0.1 1.2 0 053 0 3 68 95

4.1 10 04 2.36 2.59 56.52 9 28

10.0 0 28 100